

*Application  
for  
United States Letters Patent*

**To all whom it may concern:**

Be it known that        **we, William C. Olson and Paul J. Maddon**

have invented certain new and useful improvements in

**COMPOSITIONS AND METHODS FOR INHIBITION OF HIV-1 INFECTION**

of which the following is a full, clear and exact description.

**COMPOSITIONS AND METHODS FOR INHIBITION OF HIV-1 INFECTION**

5 This application is a continuation-in-part of and claims the benefit of PCT International Application No. PCT/US01/02633, filed January 26, 2001, U.S. Provisional Application No. 60/266,738, filed February 6, 2001, and U.S. Serial No. 09/663,219, filed September 15, 2000, the contents of which  
10 are hereby incorporated by reference into this application.

Throughout this application, various publications are referenced within parentheses. Disclosures of these publications in their entireties are hereby incorporated by  
15 reference into this application to more fully describe the state of the art to which this invention pertains. Full bibliographic citations for these references may be found immediately preceding the claims.

20 **Background of the Invention**

Infection of cells by human immunodeficiency virus type 1 (HIV-1) is mediated by the viral envelope (env) glycoproteins gp120 and gp41, which are expressed as a noncovalent, oligomeric complex on the surface of virus and  
25 virally infected cells. HIV-1 entry into target cells proceeds at the cell surface through a cascade of events that include (1) binding of the viral surface glycoprotein gp120 to cell surface CD4, which is the primary receptor for HIV-1, (2) env binding to fusion coreceptors such as CCR5  
30 and CXCR4, and (3) multiple conformational changes in gp41. During fusion, gp41 adopts transient conformations that include a prehairpin fusion intermediate that ultimately

folds into a conformation capable of mediating fusion. These events culminate in fusion of the viral and cellular membranes and the subsequent introduction of the viral genome into the target cell. A similar sequence of molecular events is required for infection to spread via fusion of infected and uninfected cells. Each stage of the viral entry process can be targeted for therapeutic intervention.

HIV-1 attachment can be inhibited both by agents that bind the viral envelope glycoproteins and by agents that bind human CD4. Notably, HIV-1 attachment can be inhibited by compounds that incorporate the gp120-binding domains of human CD4 and molecular mimics thereof [1-7]. Because this interaction between gp120 and CD4 is essential for virus infection, CD4-based molecules have the potential to target most if not all strains of HIV-1. In addition, viruses have limited ability to develop resistance to such molecules.

The determinants for gp120 binding map to the first extracellular domain (D1) on CD4 [1], and the amino acids critical for binding center on a loop comprising amino acids 36-47. Potent HIV-1 inhibitory activity has been reproduced in a 27-amino acid peptide that mimics this loop and surrounding structures [7].

A number of recombinant CD4-based molecules have been developed and tested for clinical activity in man. The first of these contained the four extracellular domains (D1-D4) of CD4 but lacked the transmembrane and intracellular regions. This molecule, termed soluble CD4 (sCD4), demonstrated excellent tolerability when administered to

humans at doses ranging to 10 mg/kg [8,9]. Transient reductions in plasma levels of infectious HIV-1 were observed in certain patients treated with sCD4. The short half-life of sCD4 in humans (45 minutes following intravenous administration) was identified as one obstacle to using this agent for chronic therapy.

Second-generation CD4-based proteins were developed with increased serum half-life. These CD4-immunoglobulin fusion proteins comprised the D1D2 domains of CD4 genetically fused to the hinge CH2 and CH3 regions of human IgG molecules. These divalent proteins derive HIV-1 neutralizing capacity from their CD4 domains and Fc effector functions from the IgG molecule. A CD4-IgG1 fusion protein was shown to have excellent tolerability and improved pharmacokinetics in Phase I clinical testing [10]. The antiviral evaluations were inconclusive.

More recently, a third-generation tetravalent CD4-IgG2 fusion protein was developed that comprises the D1D2 domains of CD4 genetically fused to the heavy and light chain constant regions of human IgG2. This agent binds the HIV-1 envelope glycoprotein gp120 with nanomolar affinity [5] and may inhibit virus attachment both by receptor blockade and by detaching gp120 from the virion surface, thereby irreversibly inactivating the virus. In standard PBMC-based neutralization assays, CD4-IgG2 neutralized primary HIV-1 isolates derived from all major subtypes and outlier groups. The CD4-IgG2 concentrations required to achieve a 90% reduction in viral infectivity, the in vitro IC90, were approximately 15-20 µg/ml [11], concentrations that are readily achievable in vivo. CD4-IgG2 was similarly effective

in neutralizing HIV-1 obtained directly from the plasma of seropositive donors in an ex vivo assay, indicating that this agent is active against the diverse viral quasiespecies that are encountered clinically [12]. CD4-IgG2 also provided protection against infection by primary isolates in the hu-PBL-SCID mouse model of HIV-1 infection [13]. Recent analyses have demonstrated that CD4-IgG2's ability to neutralize primary viruses is independent of their coreceptor usage [14].

Compared with mono- or divalent CD4-based proteins, CD4-IgG2 has consistently demonstrated as much as 100-fold greater potency at inhibiting primary HIV-1 isolates [5,12,14,15]. The heightened potency may derive from CD4-IgG2's ability to bind virions with increased valency/avidity and its steric juxtaposition of two gp120 binding sites on each Fab-like arm of the immunoglobulin molecule. The larger Fab-like arms of CD4-IgG2 are also more likely to span HIV-1 envelope spikes on the virion. In a variety of preclinical models, CD4-IgG2's anti-HIV-1 activity has been shown to compare favorably with those of the rare human monoclonal antibodies that broadly and potently neutralize primary HIV-1 isolates [5,11,14,15]. In addition, CD4-IgG2 therapy is in principle less susceptible to the development of drug-resistant viruses than therapies employing anti-env monoclonal antibodies or portions of the highly mutable HIV-1 envelope glycoproteins. These properties suggest that CD4-IgG2 may have clinical utility as an agent that neutralizes cell-free virus before it has the opportunity to establish new rounds of infection. In addition to treatment, CD4-IgG2 may have utility in preventing infection resulting from occupational, perinatal or other exposure to HIV-1.

In Phase I clinical testing, single-dose CD4-IgG2 demonstrated excellent pharmacology and tolerability. In addition, measurable antiviral activity was observed by each of two measures. First, a statistically significant acute reduction in plasma HIV RNA was observed following administration of a single 10 mg/kg dose. In addition, sustained reductions in plasma levels of infectious HIV were observed in each of two patients tested. Taken together, these observations indicate that CD4-IgG2 possesses antiviral activity in humans [16].

In addition to CD4-based proteins and molecular mimics thereof, HIV-1 attachment can also be inhibited by antibodies and nonpeptidyl molecules. Known inhibitors include (1) anti-env antibodies such as IgG1b12 and F105 [17,18], (2) anti-CD4 antibodies such as OKT4A, Leu 3a, and humanized versions thereof [19,20], and (3) nonpeptidyl agents that target either gp120 or CD4 [21], [22-24]. The latter group of compounds includes aurintricarboxylic acids, polyhydroxycarboxylates, sulfonic acid polymers, and dextran sulfates.

Several agents have been identified that block HIV-1 infection by targeting gp41 fusion intermediates. These inhibitors may interact with the fusion intermediates and prevent them from folding into final fusogenic conformations. The first such agents to be identified comprised synthetic or recombinant peptides corresponding to portions of the gp41 ectodomain predicted to form hydrophobic alpha helices. One such region is present in both the amino and carboxy segments of the extracellular portion of gp41, and recent crystallographic evidence

suggests that these regions interact in the presumed fusogenic conformation of gp41 [25,26]. HIV-1 infection can be inhibited by agents that bind to either N- or C-terminal gp41 epitopes that are exposed during fusion. These agents include the gp41-based peptides T-20 (formerly known as DP178), T-1249, DP107, N34, C28, and various fusion proteins and analogues thereof [27-33]. Other studies have identified inhibitors that comprise non-natural D-peptides and nonpeptidyl moieties [34,35]. Clinical proof-of-concept for this class of inhibitors has been provided by T-20, which reduced plasma HIV RNA levels by as much as 2 logs in Phase I/II human clinical testing [36]. The broad antiviral activity demonstrated for this class of inhibitors reflects the high degree of gp41 sequence conservation amongst diverse strains of HIV-1.

Recent studies [37] have demonstrated the possibility of raising antibodies against HIV-1 fusion intermediates. This work employed "fusion-competent" HIV vaccine immunogens that capture transient fusion intermediates formed upon interaction of gp120/gp41 with CD4 and fusion coreceptors. The immunogens used in these studies were formalin-fixed cocultures of cells that express HIV-1 gp120/gp41 and cells that express human CD4 and CCR5 but not CXCR4. The antibodies elicited by the vaccines demonstrated unprecedented breadth and potency in inhibiting primary HIV-1 isolates regardless of their coreceptor usage, indicating that the antibodies were raised against structures such as gp41 fusion intermediates that are highly conserved and transiently exposed during HIV-1 entry. This class of antibodies does not include the anti-gp41 monoclonal antibody known as 2F5, which interacts with an epitope that

is constitutively presented on virus particles prior to fusion [38].

Previously, synergistic inhibition of HIV-1 entry has been demonstrated using certain anti-env antibodies used in combination with other anti-env antibodies [39-44], anti-CD4 antibodies [45], or CD4-based proteins [6]. Similarly, synergies have been observed using anti-CCR5 antibodies used in combination with other anti-CCR5 antibodies, CC-chemokines, or CD4-based proteins [46]. Our prior studies described in U.S. Serial No. 09/493,346 examined combinations of fusion inhibitors and attachment inhibitors. Our prior studies described in PCT International Application No. PCT/US99/30345, WO 00/35409, published June 22, 2000 examined combinations of HIV-1 attachment inhibitors and CCR5 coreceptor inhibitors. However, no prior studies have examined the combination of fusion inhibitors and CCR5 coreceptor inhibitors, nor the triple combination of fusion inhibitors, CCR5 coreceptor inhibitors and HIV-1 attachment inhibitors.

#### **Summary of the Invention**

This invention provides a composition which comprises an admixture of two compounds, wherein: (a) one compound is an antibody or portion thereof which binds to a CCR5 receptor; and (b) one compound retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate; wherein the relative mass ratio of the



compounds in the admixture ranges from about 100:1 to about 1:100, the composition being effective to inhibit HIV-1 infection of the CD4+ cell.

5 This invention provides a composition which comprises an admixture of three compounds, wherein: (a) one compound is an antibody or portion thereof which binds to a CCR5 receptor; (b) one compound retards attachment of HIV-1 to a CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell; and (c) one compound retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate; wherein the relative mass ratio of any two of the compounds in the admixture ranges from about 100:1 to about 1:100, the composition being effective to inhibit HIV-1 infection of the CD4+ cell.

10 This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with an amount of the composition of the subject invention effective to inhibit HIV-1 infection of the CD4+ cell so as to thereby inhibit HIV-1 infection of the CD4+ cell.

15 This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with (1) an amount of an antibody which binds to a CCR5 receptor and (2) an amount of a compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate, so as to thereby inhibit HIV-

1 infection of the CD4+ cell.

5 This invention provides a method of inhibiting HIV-1  
infection of a CD4+ cell which comprises contacting the CD4+  
cell with (1) an amount of an antibody which binds to a CCR5  
receptor, (2) an amount of a compound which retards  
10 attachment of HIV-1 to the CD4+ cell by retarding binding of  
HIV-1 gp120 envelope glycoprotein to CD4 on the surface of  
the CD4+ cell effective to inhibit HIV-1 infection of the  
CD4+ cell, and (3) an amount of a compound which retards  
15 gp41 from adopting a conformation capable of mediating  
fusion of HIV-1 to a CD4+ cell by binding noncovalently to  
an epitope on a gp41 fusion intermediate, so as to thereby  
inhibit HIV-1 infection of the CD4+ cell.

## Brief Description of the Figures

### Figure 1

Synergistic inhibition of HIV-1 entry

5 CD4-IgG2 (--■--), T-20 (--●--), and a 25:1 CD4-IgG2:T-20  
combination (···▲···) were analyzed for inhibition of HIV-1  
entry in an env-mediated membrane fusion (RET) assay.  
Inhibitors were added to a mix of HeLa-Env<sub>JR-FL</sub><sup>+</sup> and PM1 cells  
previously labeled with F18 and R18 respectively.  
10 Fluorescence RET was measured after 4h of incubation, and  
percent inhibition was calculated as described [19]. Results  
are mean values from three independent experiments. The data  
were analyzed according to the median effect principle  
described in Equation (1). The best-fit parameters for K and  
15 m are 0.31 µg/ml and 0.73 for CD4-IgG2, 0.017 µg/ml and 0.92  
for T-20, and 0.11 µg/ml and 1.0 for their combination.  
These curves are plotted and indicate a reasonable goodness-  
of-fit between experiment and theory ( $r^2 = 0.983, 0.998, \text{ and } 0.996$  for  
20 CD4-IgG2, T-20, and their combination, respectively). To normalize for the differences in potencies  
of the compounds, separate concentrations scales are used  
for CD4-IgG2 and the 25:1 CD4-IgG2:T-20 mixture and for T-  
20, as indicated.

### Figure 2

25 Combination indices for inhibition of HIV-1 entry by  
combinations of CD4-IgG2 and T-20. CD4-IgG2, T-20 and fixed  
mass ratios thereof were analyzed in the RET assay for the  
ability to inhibit env-mediated membrane fusion. The 25:1  
30 (high) combination examined 10 three-fold serial dilutions  
of 250 µg/ml CD4-IgG2, 10 µg/ml T-20 and their combination.  
The 25:1 (low) combination examined 10 three-fold serial

dilutions of 50 µg/ml CD4-IgG2, 2 µg/ml T-20 and their combination. The 5:1 combination examined 10 three-fold serial dilutions of 50 µg/ml CD4-IgG2, 2 µg/ml T-20, and their combination. The 1:1 combination examined 10 three-fold serial dilutions of 10 µg/ml CD4-IgG2, 10 µg/ml T-20 and their combination. Inhibition data from three or more independent assays were averaged prior to analysis. Dose-response curves for the various inhibitors and combinations were fit to Equation (1), which was then rearranged to calculate the inhibitor concentrations required to effect a given percent inhibition. The concentrations of the individual agents in an inhibitory mixture were calculated from their known mass ratios. These values were then used to calculate the Combination Index (CI) according to Equation (2).  $CI < 1$  indicates synergy,  $CI = 1$  indicates additive effects, and  $CI > 1$  indicates antagonism.

### Figure 3

Dose reductions observed for synergistic combinations of CD4-IgG2 and T-20. CD4-IgG2, T-20 and a 25:1 fixed mass ratio thereof were tested in the RET assay for the ability to inhibit env-mediated membrane fusion. Inhibition data from six independent assays were averaged. K and m were determined by curve-fitting the dose-response curves, and Equation (1) was rearranged to allow calculation of c for a given f for the single agents and their combination. Dose Reduction is the ratio of the inhibitor concentrations required to achieve a given degree of inhibition when the inhibitor is used alone v. in a synergistic combination.

### Figure 4

Dose reductions observed for combinations of CD4-IgG2, PRO

140, PA12 and T-20. The agents were tested individually and in combination for the ability to inhibit HIV env-mediated membrane fusion in the RET assay. a.) CD4-IgG2, PA12, T-20 and a ~1:1:10 fixed molar ratio thereof. b.) CD4-IgG2, PRO 140, T-20 and a ~2:1:20 fixed molar ratio thereof, c.) CD4-IgG2, PRO 140, T-20 and a ~4:1:30 fixed molar ratio thereof, and d.) PRO 140, T-20 and a 1:30 fixed molar ratio thereof where Dose Reduction is the ratio of the inhibitor concentrations required to achieve a given degree of inhibition when the inhibitor is used alone v. in a synergistic combination. 6-8 three-fold serial dilutions of a.) 125 nM CD4-IgG2, 167 nM PA12, 1100 nM T-20 and their combination, b.) 125 nM CD4-IgG2, 67 nM PRO 140, 1100 nM T-20 and their combination, c.) 125 nM CD4-IgG2, 33 nM PRO 140, 1100 nM T-20 and their combination, and d.) 36 nM PRO 140, 1100 nM T-20 and their combination were examined. The inhibitor concentrations required to effect a given percent inhibition were calculated. The concentrations of the individual agents in an inhibitory mixture were calculated from their known molar ratios. These values were then used to calculate the Combination Index (CI) according to Equation (2).  $CI < 1$  indicates synergy,  $CI = 1$  indicates additive effects, and  $CI > 1$  indicates antagonism.

Figure 5:

Triple combination of PRO 542, PRO 140 and T-20 Synergistically Blocks HIV-1 Entry. PRO 542, PRO 140 and T-20 were used alone and in ~3:1:30 molar combination to inhibit HIV-1<sub>JR-FL</sub> env-mediated cell-cell fusion. The methodology for this assay is described in Litwin et al. (67).

Figure 6

Synergistic inhibition of HIV-1 entry

CD4-IgG2 (--■--), T-20 (--●--), and a 25:1 CD4-IgG2:T-20 combination (···▲···) were analyzed for inhibition of HIV-1 entry in an env-mediated membrane fusion (RET) assay. Inhibitors were added to a mix of HeLa-Env<sub>JR-FL</sub><sup>+</sup> and PM1 cells previously labeled with F18 and R18 respectively. Fluorescence RET was measured after 4h of incubation, and percent inhibition was calculated as described [19]. Results are mean values from three independent experiments. The data were analyzed according to the median effect principle described in Equation (1). The best-fit parameters for K and m are 0.31 µg/ml and 0.73 for CD4-IgG2, 0.017 µg/ml and 0.92 for T-20, and 0.11 µg/ml and 1.0 for their combination. These curves are plotted and indicate a reasonable goodness-of-fit between experiment and theory ( $r^2 = 0.983, 0.998, \text{ and } 0.996$  for CD4-IgG2, T-20, and their combination, respectively). To normalize for the differences in potencies of the compounds, separate concentrations scales are used for CD4-IgG2 and the 25:1 CD4-IgG2:T-20 mixture and for T-20, as indicated.

Figure 7

Combination indices for inhibition of HIV-1 entry by combinations of CD4-IgG2 and T-20. CD4-IgG2, T-20 and fixed mass ratios thereof were analyzed in the RET assay for the ability to inhibit env-mediated membrane fusion. The 25:1 (high) combination examined 10 three-fold serial dilutions of 250 µg/ml CD4-IgG2, 10 µg/ml T-20 and their combination. The 25:1 (low) combination examined 10 three-fold serial dilutions of 50 µg/ml CD4-IgG2, 2 µg/ml T-20 and their combination. The 5:1 combination examined 10 three-fold

serial dilutions of 50  $\mu\text{g/ml}$  CD4-IgG2, 2  $\mu\text{g/ml}$  T-20, and their combination. The 1:1 combination examined 10 three-fold serial dilutions of 10  $\mu\text{g/ml}$  CD4-IgG2, 10  $\mu\text{g/ml}$  T-20 and their combination. Inhibition data from three or more independent assays were averaged prior to analysis. Dose-response curves for the various inhibitors and combinations were fit to Equation (1), which was then rearranged to calculate the inhibitor concentrations required to effect a given percent inhibition. The concentrations of the individual agents in an inhibitory mixture were calculated from their known mass ratios. These values were then used to calculate the Combination Index (CI) according to Equation (2).  $\text{CI} < 1$  indicates synergy,  $\text{CI} = 1$  indicates additive effects, and  $\text{CI} > 1$  indicates antagonism.

#### Figure 8

Dose reductions observed for synergistic combinations of CD4-IgG2 and T-20. CD4-IgG2, T-20 and a 25:1 fixed mass ratio thereof were tested in the RET assay for the ability to inhibit env-mediated membrane fusion. Inhibition data from six independent assays were averaged. K and m were determined by curve-fitting the dose-response curves, and Equation (1) was rearranged to allow calculation of c for a given f for the single agents and their combination. Dose Reduction is the ratio of the inhibitor concentrations required to achieve a given degree of inhibition when the inhibitor is used alone v. in a synergistic combination.

#### Figure 9

Inhibition of HIV-1<sub>JR-FL</sub> virus-cell fusion (A) and cell-cell fusion (B-D) with PRO 542, T-20 and combinations thereof. The PRO 542:T-20 molar ratio was 1:2 (A and C) or 1:10 (B).

The concentrations of PRO 542 and T-20 in the mixtures are plotted for the purposes of illustrating dose reductions (A and B) or lack thereof (C). In the washout assay (C), the drugs were pre-incubated with HeLa-Env cells for 2 h at 25 °C prior to washing, warming and addition of PM1 cells. In the cell-cell preincubation assay (D), HeLa-Env and PM1 cells were co-incubated for 2 h at 25 °C prior to the addition of drugs and warming to 37 °C. The values represent the averages of independent assays performed in triplicate (A,B) or duplicate (C,D).

Figure 10

Combination index values and dose reductions for inhibition of HIV-1 entry with combinations of PRO542 and T-20.

Figure 11

HIV-1 entry involves at least three steps that provide targets for therapy: gp120-CD4 attachment; gp120-coreceptor interactions; gp41-mediated fusion.

Figure 12

PRO 542(CD4-IgG2) attachment inhibitor.

Figure 13

PRO 140 coreceptor inhibitor

Figure 14

T20 fusion inhibitor

Figure 15

HIV-1 virus cell fusion assay



Figure 16

Synergistic Inhibition of virus-cell fusion with PRO542 and T-20. PRO542 alone ( $\cdots\blacktriangle\cdots$ ), T-20 alone ( $--\bullet--$ ), 1:2 mix ( $--\blacksquare--$ ); (-----) PRO 542 in mix; (|||||) T-20 in mix. The virus used was HIV-1JR-FL.

Figure 17

Synergistic Inhibition of virus-cell fusion with PRO542 and T-20. PRO542 and T-20 were used in a 1:2 molar ratio

Figure 18

HIV-1 Cell-Cell Fusion Assay. Resonance Energy Transfer (RET) assay of HIV-1 membrane fusion.

Figure 19

Synergistic Inhibition of cell-cell fusion with PRO542 and T-20. PRO542 alone ( $\cdots\blacktriangle\cdots$ ), T-20 alone ( $--\bullet--$ ), 1:10 mix ( $--\blacksquare--$ ); (-----) PRO 542 in mix; (|||||) T-20 in mix. The virus used was HIV-1JR-FL.

Figure 20

Synergistic Inhibition of cell-cell fusion with PRO542 and T-20 in 1:2, 1:10 and 1:50 ratios.

Figure 21

PRO140, PRO542 and T-20 Triple Combination Synergistically Blocks HIV-1 Entry. PRO140 alone ( $\cdots\blacklozenge\cdots$ ), PRO542 alone ( $\cdots\blacktriangle\cdots$ ), T-20 alone ( $--\bullet--$ ), 1:3:30 mix ( $--\blacksquare--$ ); (\_\_\_\_\_) PRO 140 in mix; (|||||) PRO542 in mix; (-----) T-20 in mix.

Figure 22

PRO140, PRO542 and T-20 Triple Combination Synergistically Blocks HIV-1 Entry. PRO140, PRO542 and T-20 used in a 1:3:30 molar ratio.

5 Figure 23

PRO542 does not potentiate T-20 activity in the absence of coreceptor. PRO542 alone ( $\cdots\blacktriangle\cdots$ ), T-20 alone ( $--\bullet--$ ), PRO542:T-20 cocktail ( $--\blacksquare--$ ); ( $-----$ ) PRO542 in cocktail.

10 Figure 24

Formation of prehairpin intermediate requires CD4, coreceptor and 37°C. ( $--\bullet--$ ) T-20 standard assay; ( $--\bigcirc--$ ) T-20, 25°C preincubation; ( $\cdots\blacktriangle\cdots$ ) PRO542 standard assay; ( $--\Delta--$ ) PRO542, 25°C preincubation;

15 Figure 25

Formation of prehairpin intermediate requires CD4, coreceptor and 37°C. ( $--\bullet--$ ) T-20 standard assay; ( $--\bigcirc--$ ) T-20 temperature shift washout assay.

20 Figure 26

Possible mechanism of synergy: PRO542 increases the half-life of the T-20 targets.

25 Figure 27

Possible mechanism of synergy: PRO542 increases the half-life of the T-20 targets.

Figure 28

Synergistic inhibition of HIV-1 entry: PRO 542, T-1249, and a 1:10 molar combination (4:1 mass combination) of PRO 542:T-1249 were analyzed for inhibition of HIV-1 entry in an env-mediated membrane fusion (RET) assay. Inhibitors were added to a mix of HeLa-EnvJR-FL<sup>+</sup> and PM1 cells previously labeled with F18 and R18 respectively. Fluorescence RET was measured after 4 hours of incubation, and percent inhibition was calculated as described in Litwin, et al. (J. Virol. 70: 6437, 1996). The concentrations of PRO 542 and T-1249 present in the cocktail are derived from the curve fit of the data and are shown for the purposes of illustrating dose reductions.

Figure 29

Combination indices and dose reductions observed for a 1:10 molar combination of PRO 542 and T-1249. Compounds were analyzed as described in Figure 28. Combination Index values were calculated according to the median effect principle. Dose Reduction is the ratio of the inhibitor concentrations required to achieve a given degree of inhibition when the inhibitor is used alone verses in combination.

**Detailed Description of the Invention**

The plasmids CD4-IgG2-HC-pRcCMV and CD4-kLC-pRcCMV were deposited pursuant to, and in satisfaction of, the requirements of the Budapest Treaty on the International Recognition of the Deposit of Microorganisms (the "Budapest Treaty") for the Purposes of Patent Procedure with the American Type Culture Collection (ATCC), 10801 University Blvd, Manassas, VA 20110-2209 under ATCC Accession Nos. 75193 and 75194, respectively. The plasmids were deposited with ATCC on Jan. 30, 1992. The plasmid designated pMA243 was similarly deposited in accordance with the Budapest Treaty with ATCC under Accession No. 75626 on December 16, 1993.

The murine hybridomas PA8, PA9, PA10, PA11, PA12 and PA14 were deposited pursuant to, and in satisfaction of, the requirements of the Budapest Treaty on the International Recognition of the Deposit of Microorganisms (the "Budapest Treaty") for the Purposes of Patent Procedure with the American Type Culture Collection (ATCC), 10801 University Blvd, Manassas, VA 20110-2209 under the following ATCC Accession Nos.: PA8 (ATCC No. HB-12605), PA9 (ATCC No. HB-12606), PA10 (ATCC No. HB-12607), PA11 (ATCC No. HB-12608), PA12 (ATCC No. HB-12609) and PA14 (ATCC No. HB-12610). The hybridomas were deposited on December 2, 1998.

As used herein, the following standard abbreviations are used throughout the specification to indicate specific amino acids:

A=ala=alanine  
N=asn=asparagine

R=arg=arginine  
D=asp=aspartic acid

C=cys=cysteine	Q=gln=glutamine
E=glu=glutamic acid	G=gly=glycine
H=his=histidine	I=ile=isoleucine
L=leu=leucine	K=lys=lysine
5 M=met=methionine	F=phe=phenylalanine
P=pro=proline	S=ser=serine
T=thr=threonine	W=trp=tryptophan
Y=tyr=tyrosine	V=val=valine

10 This invention provides a composition which comprises an admixture of two compounds, wherein: (a) one compound is an antibody or portion thereof which binds to a CCR5 receptor; and (b) one compound retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate; wherein the relative mass ratio of the compounds in the admixture ranges from about 100:1 to about 1:100, the composition being effective to inhibit HIV-1 infection of the CD4+ cell.

20 This invention provides a composition which comprises an admixture of three compounds, wherein: (a) one compound is an antibody or portion thereof which binds to a CCR5 receptor; (b) one compound retards attachment of HIV-1 to a CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell; and (c) one compound retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate; wherein the relative mass ratio of any two of the compounds in the admixture ranges from about 100:1 to about 1:100, the composition being effective to inhibit HIV-

1 infection of the CD4+ cell.

This invention provides a composition which comprises an admixture of two compounds, wherein one compound retards attachment of HIV-1 to a CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell and the other compound retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate, wherein the relative mass ratio of the compounds in the admixture ranges from about 100:1 to about 1:100, the composition being effective to inhibit HIV-1 infection of the CD4+ cell.

As used herein, "HIV-1" means the human immunodeficiency virus type-1. HIV-1 includes but is not limited to extracellular virus particles and the forms of HIV-1 associated with HIV-1 infected cells. HIV-1<sub>JR-FL</sub> is a strain that was originally isolated at autopsy from the brain tissue of an AIDS patient [47]. The virus was co-cultured with lectin-stimulated normal human peripheral blood mononuclear cells. The virus has been cloned and the DNA sequences of its envelope glycoproteins are known (Genbank Accession #U63632). In terms of sensitivity to inhibitors of viral entry, HIV-1<sub>JR-FL</sub> is known to be highly representative of primary HIV-1 isolates [11,14,15,48-50].

As used herein, "gp41 fusion intermediates" includes structures, conformations, and oligomeric states that are preferentially and transiently presented or exposed on the HIV-1 envelope glycoprotein gp41 during the process of HIV-1 env-mediated membrane fusion. These intermediates may form

upon interaction of HIV-1 with cellular receptors or may be present in partially or fully occluded states on HIV-1 prior to its interaction with cellular receptors. "gp41 fusion intermediates" do not include fusogenic gp41 conformations that cannot provide targets for therapeutic intervention.

The gp41 fusion intermediates may contain multiple epitopes that are transiently exposed during fusion and can provide targets for therapeutic intervention. As used herein, an "N-terminal gp41 epitope" may comprise all or portions of the sequences from amino acid A541 to Q590. As used herein, a "C-terminal gp41 epitope" may comprise all or portions of the sequences from amino acid W628 to L663. These epitopes have the potential to form coiled-coils of interacting alpha helical segments by virtue of heptad (sequence of seven amino acids) repeats containing hydrophobic amino acids at positions 1 and 4 of the heptad. The amino acid numbering system is for the HxB2 isolate of HIV-1 (Genbank Protein Accession No. AAB50262). Because of the sequence variability of HIV-1 envelope proteins, the composition, size and precise location of such sequences may be different for different viral isolates. The gp41 fusion intermediates may also present other linear or conformational epitopes that are transiently expressed during HIV-1 entry. An inhibitor may target multiple epitopes present on gp41 fusion intermediates. Alternatively, separate inhibitors may be used in combination to target one or more epitopes present on gp41 fusion intermediates.

As used herein, "fusogenic" means capable of mediating membrane fusion. As used herein, "HIV-1 fusion coreceptor" means a cellular receptor that mediates fusion between the

target cell expressing the receptor and HIV-1 or an HIV-1 envelope glycoprotein\* cell. HIV-1 fusion co-receptors include but are not limited to CCR5, CXCR4 and other chemokine receptors. As used herein, "fusion" means the joining or union of the lipid bilayer membranes found on mammalian cells or viruses such as HIV-1. This process is distinguished from the attachment of HIV-1 to a target cell. Attachment is mediated by the binding of the HIV-1 exterior glycoprotein to the human CD4 receptor, which is not a fusion co-receptor.

As used herein, "retards" means that the amount is reduced. As used herein, "attachment" means the process that is mediated by the binding of the HIV-1 envelope glycoprotein to the human CD4 receptor, which is not a fusion co-receptor. As used herein, "CD4" means the mature, native, membrane-bound CD4 protein comprising a cytoplasmic domain, a hydrophobic transmembrane domain, and an extracellular domain which binds to the HIV-1 gp120 envelope glycoprotein.

As used herein, "epitope" means a portion of a molecule or molecules that form a surface for binding antibodies or other compounds. The epitope may comprise contiguous or noncontiguous amino acids, carbohydrate or other nonpeptidyl moieties or oligomer-specific surfaces.

The compounds of the subject invention have shown to demonstrate a synergistic effect. As used herein, "synergistic" means that the combined effect of the compounds when used in combination is greater than their additive effects when used individually.



In one embodiment of the composition of this invention, the compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell is a CD4-based protein. As used herein, "CD4-based protein" means any protein comprising at least one sequence of amino acid residues corresponding to that portion of CD4 which is required for CD4 to form a complex with the HIV-1 gp120 envelope glycoprotein.

In one embodiment the CD4-based protein is a CD4-immunoglobulin fusion protein. In one embodiment the CD4-immunoglobulin fusion protein is CD4-IgG2, wherein the CD4-IgG2 comprises two heavy chains and two light chains, wherein the heavy chains are encoded by an expression vector designated CD4-IgG2HC-pRcCMV (ATCC Accession No. 75193) and the light chains are encoded by an expression vector designated CD4-kLC-pRcCMV (ATCC Accession No. 75194). As used herein, CD4-IgG2 is also referred to as PRO 542.

In one embodiment of the composition of this invention, the compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell is a protein, the amino acid sequence of which comprises that of a protein found in HIV-1 as an envelope glycoprotein. In one embodiment, the protein binds to an epitope of CD4 on the surface of the CD4+ cell. In one embodiment the envelope glycoprotein is selected from the group consisting of gp120, gp160, and gp140.

In one embodiment of the composition of this invention, the compound which retards the attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell is an antibody or portion of an antibody. In one embodiment, the antibody is a monoclonal antibody. In one embodiment, the monoclonal antibody is a human, humanized or chimeric antibody. In one embodiment, the portion of the antibody is a Fab fragment of the antibody. In one embodiment, the portion of the antibody comprises the variable domain of the antibody. In one embodiment, the portion of the antibody comprises a CDR portion of the antibody. In one embodiment, the monoclonal antibody is an IgG, IgM, IgD, IgA, or IgE monoclonal antibody.

As used herein, "antibody" means an immunoglobulin molecule comprising two heavy chains and two light chains and which recognizes an antigen. The immunoglobulin molecule may derive from any of the commonly known classes, including but not limited to IgA, secretory IgA, IgG and IgM. IgG subclasses are also well known to those in the art and include but are not limited to human IgG1, IgG2, IgG3 and IgG4. It includes, by way of example, both naturally occurring and non-naturally occurring antibodies. Specifically, "antibody" includes polyclonal and monoclonal antibodies, and monovalent and divalent fragments thereof. Furthermore, "antibody" includes chimeric antibodies, wholly synthetic antibodies, single chain antibodies, and fragments thereof. The antibody may be a human or nonhuman antibody. A nonhuman antibody may be humanized by recombinant methods to reduce its immunogenicity in man. Methods for humanizing antibodies are known to those skilled in the art.

This invention provides humanized forms of the above antibodies. As used herein, "humanized" describes antibodies wherein some, most or all of the amino acids outside the CDR regions are replaced with corresponding amino acids derived from human immunoglobulin molecules. In one embodiment of the humanized forms of the antibodies, some, most or all of the amino acids outside the CDR regions have been replaced with amino acids from human immunoglobulin molecules but where some, most or all amino acids within one or more CDR regions are unchanged. Small additions, deletions, insertions, substitutions or modifications of amino acids are permissible as long as they would not abrogate the ability of the antibody to bind a given antigen. Suitable human immunoglobulin molecules would include IgG1, IgG2, IgG3, IgG4, IgA and IgM molecules. A "humanized" antibody would retain a similar antigenic specificity as the original antibody, i.e., in the present invention, the ability to bind CCR5.

One skilled in the art would know how to make the humanized antibodies of the subject invention. Various publications, several of which are hereby incorporated by reference into this application, also describe how to make humanized antibodies. For example, the methods described in United States Patent No. 4,816,567 (58) comprise the production of chimeric antibodies having a variable region of one antibody and a constant region of another antibody.

United States Patent No. 5,225,539 (59) describes another approach for the production of a humanized antibody. This patent describes the use of recombinant DNA technology to produce a humanized antibody wherein the CDRs of a variable

region of one immunoglobulin are replaced with the CDRs from an immunoglobulin with a different specificity such that the humanized antibody would recognize the desired target but would not be recognized in a significant way by the human subject's immune system. Specifically, site directed mutagenesis is used to graft the CDRs onto the framework.

Other approaches for humanizing an antibody are described in United States Patent Nos. 5,585,089 (60) and 5,693,761 (61) and WO 90/07861 which describe methods for producing humanized immunoglobulins. These have one or more CDRs and possible additional amino acids from a donor immunoglobulin and a framework region from an accepting human immunoglobulin. These patents describe a method to increase the affinity of an antibody for the desired antigen. Some amino acids in the framework are chosen to be the same as the amino acids at those positions in the donor rather than in the acceptor. Specifically, these patents describe the preparation of a humanized antibody that binds to a receptor by combining the CDRs of a mouse monoclonal antibody with human immunoglobulin framework and constant regions. Human framework regions can be chosen to maximize homology with the mouse sequence. A computer model can be used to identify amino acids in the framework region which are likely to interact with the CDRs or the specific antigen and then mouse amino acids can be used at these positions to create the humanized antibody.

The above patents 5,585,089 and 5,693,761, and WO 90/07861 (62) also propose four possible criteria which may be used in designing the humanized antibodies. The first proposal was that for an acceptor, use a framework from a particular

human immunoglobulin that is unusually homologous to the donor immunoglobulin to be humanized, or use a consensus framework from many human antibodies. The second proposal was that if an amino acid in the framework of the human immunoglobulin is unusual and the donor amino acid at that position is typical for human sequences, then the donor amino acid rather than the acceptor may be selected. The third proposal was that in the positions immediately adjacent to the 3 CDRs in the humanized immunoglobulin chain, the donor amino acid rather than the acceptor amino acid may be selected. The fourth proposal was to use the donor amino acid residue at the framework positions at which the amino acid is predicted to have a side chain atom within 3Å of the CDRs in a three dimensional model of the antibody and is predicted to be capable of interacting with the CDRs. The above methods are merely illustrative of some of the methods that one skilled in the art could employ to make humanized antibodies.

In one embodiment, the monoclonal antibody binds to an HIV-1 envelope glycoprotein. In one embodiment, the HIV-1 envelope glycoprotein is selected from the group consisting of gp120 and gp160.

In one embodiment, the HIV-1 envelope glycoprotein is gp120 and the monoclonal antibody which binds to gp120 is IgG1b12 or F105. IgG1b12 is listed as item #2640 in the NIH AIDS Research and Reference Reagent Program Catalog. F105 is listed as item #857 in the NIH AIDS Research and Reference Reagent Program Catalog.

In one embodiment, the antibody binds to an epitope of CD4

on the surface of the CD4+ cell.

5 In one embodiment of the composition of this invention, the compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell is a peptide. In one embodiment of the composition of this invention, the compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to  
10 CD4 on the surface of the CD4+ cell is a nonpeptidyl agent. As used herein, "nonpeptidyl" means that the agent does not consist in its entirety of a linear sequence of amino acids linked by peptide bonds. A nonpeptidyl agent may, however, contain one or more peptide bonds.

15 In one embodiment of the composition of this invention, the compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate is an antibody. In one embodiment the antibody is a monoclonal antibody. In one embodiment, the antibody is  
20 a polyclonal antibody.

25 In one embodiment of the composition of this invention, the compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate is a peptide.

30 In one embodiment of the composition of this invention, the compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by

binding noncovalently to an epitope on a gp41 fusion intermediate is a fusion protein which comprises a peptide which includes but is not limited to T-20 (SEQ ID NO: 1), DP107 (SEQ ID NO: 2), N34 (SEQ ID NO: 3), C28 (SEQ ID NO: 4), and N34(L6)C28 (SEQ ID NO: 5). In one embodiment the peptide is selected from the group consisting of T-20 (SEQ ID NO: 1), DP107 (SEQ ID NO: 2), N34 (SEQ ID NO: 3), C28 (SEQ ID NO: 4), N34(L6)C28 (SEQ ID NO: 5), and T-1249 (SEQ ID NO: 6). In one embodiment, the peptide is T-20 (SEQ ID NO: 1).

As used herein, "T-20" and "DP178" are used interchangeably to denote a peptide having the following amino acid sequence: YTSLIHSLIEESQNQQEKNEQELLELDKWASLWNWF (SEQ ID NO: 1) and as described [29,32]. DP107 has the following amino acid sequence: NNLLRAIEAQQHLLQLTVWGIKQLQARILAVERYLKDQ (SEQ ID NO: 2). N34 has the following amino acid sequence: SGIVQQQNNLLRAIEAQQHLLQLTVWGIKQLQAR (SEQ ID NO: 3). C28 has the following amino acid sequence: WMEWDREINNYTSLIHSLEESQNQQEK (SEQ ID NO: 4). N34(L6)C28 has the following amino acid sequence: SGIVQQQNNLLRAIEAQQHLLQLTVWGIKQLQARS GGRGGWMEWDREINNYTSLIHSLEESQNQQEK (SEQ ID NO: 5). T-1249 has the following amino acid sequence : WQEWQKITALLEQAQIQQEKNEYELQKLDKWASLWFW (SEQ ID NO: 6).

In one embodiment of the compositions described herein, the peptide is a mutant peptide which (1) consists of amino acids having a sequence identical to that of a wildtype peptide selected from the group consisting of T-20 (SEQ ID NO: 1), DP-107 (SEQ ID NO: 2), N34 (SEQ ID NO: 3), C28 (SEQ ID NO: 4), N34(L6)C28 (SEQ ID NO: 5) and T-1249 (SEQ ID NO: 6),

except for an addition of at least one glycine residue to a 5' end of the peptide, to a 3' end of the peptide, or to both ends of the peptide and (2) retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate.

In one embodiment, the compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate is a fusion protein which comprises a peptide selected from the group consisting of T-20 (SEQ ID NO: 1), DP107 (SEQ ID NO: 2), N34 (SEQ ID NO: 3), C28 (SEQ ID NO: 4), N34(L6)C28 (SEQ ID NO: 5), and T-1249 (SEQ ID NO:6).

In one embodiment of the compositions described herein, the peptide is selected from the group consisting of T-20 (SEQ ID NO: 1), DP107 (SEQ ID NO: 2), N34 (SEQ ID NO: 3), C28 (SEQ ID NO: 4), N34(L6)C28 (SEQ ID NO: 5), and T-1249 (SEQ ID NO:6).

In one embodiment of the compositions described herein, the peptide is T-20 (SEQ ID NO: 1). In one embodiment of the compositions described herein, the peptide is T-1249 (SEQ ID NO:6)

In one embodiment of the composition of this invention, the compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate is a non-peptidyl agent.



In one embodiment, a non-peptidyl agent of the subject invention is a small molecule. In one embodiment, the non-peptidyl agent is a compound having a molecular weight less than 500 daltons.

5 In one embodiment of the composition of this invention, the antibody which binds to a CCR5 receptor includes but is not limited to PA8 (ATCC Accession No. HB-12605), PA10 (ATCC Accession No.12607), PA11 (ATCC Accession No. HB-12608),  
10 PA12 (ATCC Accession No. HB-12609), and PA14 (ATCC Accession No. HB-12610). In one embodiment, the antibody is a monoclonal antibody. In one embodiment, the monoclonal antibody is a human, humanized or chimeric antibody. In one  
15 embodiment, the portion of the antibody is a Fab fragment of the antibody. In one embodiment, the portion of the antibody comprises the variable domain of the antibody. In one embodiment, the portion of the antibody comprises a CDR portion of the antibody. In one embodiment, the monoclonal  
20 antibody is an IgG, IgM, IgD, IgA, or IgE monoclonal antibody.

In one embodiment of the composition of this invention, the relative mass ratio of each such compound in the admixture ranges from about 25:1 to about 1:1. In one embodiment, the  
25 mass ratio is about 25:1. In one embodiment, the mass ratio is about 5:1. In one embodiment, the mass ratio is about 1:1.

30 In one embodiment of the composition of this invention, the composition is admixed with a carrier. The carriers of the subject invention include but are not limited to aerosol, intravenous, oral or topical carriers. Pharmaceutically

acceptable carriers are well known to those skilled in the art. Such pharmaceutically acceptable carriers may include but are not limited to aqueous or non-aqueous solutions, suspensions, and emulsions. Examples of non-aqueous solvents are propylene glycol, polyethylene glycol, vegetable oils such as olive oil, and injectable organic esters such as ethyl oleate. Aqueous carriers include water, alcoholic/aqueous solutions, emulsions or suspensions, saline and buffered media. Parenteral vehicles include sodium chloride solution, Ringer's dextrose, dextrose and sodium chloride, lactated Ringer's or fixed oils. Intravenous vehicles include fluid and nutrient replenishers, electrolyte replenishers such as those based on Ringer's dextrose, and the like. Preservatives and other additives may also be present, such as, for example, antimicrobials, antioxidants, chelating agents, inert gases and the like.

This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with an amount of the composition of the subject invention effective to inhibit HIV-1 infection of the CD4+ cell so as to thereby inhibit HIV-1 infection of the CD4+ cell.

In one embodiment, the CD4+ cell is present in a subject and the contacting is effected by administering the composition to the subject.

As used herein, "subject" includes any animal or artificially modified animal capable of becoming HIV-infected. Artificially modified animals include, but are not

limited to, SCID mice with human immune systems. The animals include but are not limited to mice, rats, dogs, cats, guinea pigs, ferrets, rabbits, and primates. In the preferred embodiment, the subject is a human.

5 As used herein, "administering" may be effected or performed using any of the methods known to one skilled in the art, which includes intralesional, intraperitoneal, intramuscular, subcutaneous, intravenous, liposome mediated  
10 delivery, transmucosal, intestinal, topical, nasal, oral, anal, ocular or otic delivery. The compounds may be administered separately (e.g., by different routes of administration, sites of injection, or dosing schedules) so as to combine in synergistically effective amounts in the  
15 subject.

The dose of the composition of the invention will vary depending on the subject and upon the particular route of administration used. Dosages can range from 0.1 to 100,000  
20 µg/kg. Based upon the composition, the dose can be delivered continuously, such as by continuous pump, or at periodic intervals. For example, on one or more separate occasions. Desired time intervals of multiple doses of a particular composition can be determined without undue experimentation  
25 by one skilled in the art.

As used herein, "effective dose" means an amount in sufficient quantities to either treat the subject or prevent the subject from becoming infected with HIV-1. A person of  
30 ordinary skill in the art can perform simple titration experiments to determine what amount is required to treat the subject.

In one embodiment, the effective amount of the composition comprises from about 0.000001 mg/kg body weight to about 100 mg/kg body weight of the subject.

5 This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with (1) an amount of an antibody which binds to a CCR5 receptor and (2) an amount of a compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate, so as to thereby inhibit HIV-1 infection of the CD4+ cell.

15 This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with (1) an amount of an antibody which binds to a CCR5 receptor, (2) an amount of a compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell effective to inhibit HIV-1 infection of the CD4+ cell, and (3) an amount of a compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate, so as to thereby inhibit HIV-1 infection of the CD4+ cell.

25 This invention provides a method of inhibiting HIV-1 infection of a CD4+ cell which comprises contacting the CD4+ cell with (1) an amount of a compound which retards attachment of HIV-1 to the CD4+ cell by retarding binding of HIV-1 gp120 envelope glycoprotein to CD4 on the surface of the CD4+ cell effective to inhibit HIV-1 infection of the

CD4+ cell and (2) an amount of a compound which retards gp41 from adopting a conformation capable of mediating fusion of HIV-1 to a CD4+ cell by binding noncovalently to an epitope on a gp41 fusion intermediate so as to thereby inhibit HIV-1 infection of the CD4+ cell.

In one embodiment, the CD4+ cell is present in a subject and the contacting is effected by administering the compounds to the subject. In one embodiment, the compounds are administered to the subject simultaneously. In one embodiment, the compounds are administered to the subject at different times. In one embodiment, the compounds are administered to the subject by different routes of administration.

The subject invention has various applications which includes HIV treatment such as treating a subject who has become afflicted with HIV. As used herein, "afflicted with HIV-1" means that the subject has at least one cell which has been infected by HIV-1. As used herein, "treating" means either slowing, stopping or reversing the progression of an HIV-1 disorder. In the preferred embodiment, "treating" means reversing the progression to the point of eliminating the disorder. As used herein, "treating" also means the reduction of the number of viral infections, reduction of the number of infectious viral particles, reduction of the number of virally infected cells, or the amelioration of symptoms associated with HIV-1. Another application of the subject invention is to prevent a subject from contracting HIV. As used herein, "contracting HIV-1" means becoming infected with HIV-1, whose genetic information replicates in and/or incorporates into the host cells. Another application

of the subject invention is to treat a subject who has become infected with HIV-1. As used herein, "HIV-1 infection" means the introduction of HIV-1 genetic information into a target cell, such as by fusion of the target cell membrane with HIV-1 or an HIV-1 envelope glycoprotein<sup>+</sup> cell. The target cell may be a bodily cell of a subject. In the preferred embodiment, the target cell is a bodily cell from a human subject. Another application of the subject invention is to inhibit HIV-1 infection. As used herein, "inhibiting HIV-1 infection" means reducing the amount of HIV-1 genetic information introduced into a target cell population as compared to the amount that would be introduced without said composition.

This invention will be better understood from the Experimental Details that follow. However, one skilled in the art will readily appreciate that the specific methods and results discussed are merely illustrative of the invention as described more fully in the claims that follow thereafter.

## Experimental Details

### FIRST SERIES OF EXPERIMENTS

#### A. Materials and Methods

##### 1) Reagents

Purified recombinant CD4-IgG2 protein was produced by Progenics Pharmaceuticals, Inc. from plasmids CD4-IgG2-HC-pRcCMV and CD4-kLC-pRcCMV (ATCC Accession Nos. 75193 and 75194, respectively) as described [5]. HeLa-env cells were prepared by transfecting HeLa cells (ATCC Catalog # CCL-2) with HIV-1 gp120/gp41 env-expressing plasmid pMA243 as described [51]. PM1 cells are available from the National Institutes of Health AIDS Reagent Program (Catalog #3038). The T-20 peptide was synthesized using standard solid-phase Fmoc chemistry and purified and characterized as described [31,32].

##### 2) Inhibition of HIV-1 env-mediated membrane fusion

HIV-1 envelope-mediated fusion between HeLa-Env<sub>JR-FL</sub> and PM1 cells was detected using a Resonance Energy Transfer (RET) assay. Equal numbers (2x10<sup>4</sup>) of fluorescein octadecyl ester (F18)-labeled envelope-expressing cells and octadecyl rhodamine (R18)-labeled PM1 cells were plated in 96-well plates in 15% fetal calf serum in phosphate buffered saline and incubated for 4h at 37 °C in the presence of varying concentrations of CD4-IgG2, T-20 or combinations thereof. Fluorescence RET was measured with a Cytofluor plate-reader (PerSeptive Biosystems) and % RET was determined as previously described [19].

##### 3) Quantitative analysis of the synergistic, additive or

antagonistic effects of combining the agents

HIV-1 inhibition data were analyzed according to the Combination Index method of Chou and Talay [52,53]. The data are modeled according to the median-effect principle, which can be written

$$f = 1/[1 + (K/c)^m] \quad (1)$$

where  $f$  is the fraction affected/inhibited,  $c$  is concentration,  $K$  is the concentration of agent required to produce the median effect, and  $m$  is an empirical coefficient describing the shape of the dose-response curve. Equation (1) is a generalized form of the equations describing Michaelis-Menton enzyme kinetics, Langmuir adsorption isotherms, and Henderson-Hasselbalch ionization equilibria, for which  $m = 1$  in all cases. In the present case,  $K$  is equal to the  $IC_{50}$  value.  $K$  and  $m$  are determined by curve-fitting the dose-response curves.

After the best-fit parameters for  $K$  and  $m$  are obtained for the experimental agents and their combination, Equation (1) is rearranged to allow for calculation of  $c$  for a given  $f$ . The resulting table of values (e.g., Figure X) is used to calculate the Combination Index (CI) using the equation

$$CI = C_{1m}/C_1 + C_{2m}/C_2 + C_{1m}C_{2m}/C_1C_2 \quad (2)$$

where

$C_1$  = concentration of compound 1 when used alone



$C_2$  = concentration of compound 2 when used alone

$C_{1m}$  = concentration of compound 1 in the mixture

$C_{2m}$  = concentration of compound 2 in the mixture

5 All concentrations are those required to achieve a given degree of inhibition. Equation (2) is used when the molecules are mutually nonexclusive, i.e., have different sites of action. Since this is the likely scenario for inhibitors of HIV-1 attachment and gp41 fusion  
10 intermediates, Equation (2) was used for all Combination Index calculations. Mutually nonexclusive calculations provide a more conservative estimate of the degree of synergy that mutually exclusive calculations, for which the  $C_{1m}C_{2m}/C_1C_2$  term is dropped.  $CI < 1$  indicates synergy,  $CI = 1$  indicates purely additive effects, and  $CI > 1$  indicates antagonism. In general, CI values are most relevant at the higher levels of inhibition that are required to achieve a measurable clinical benefit.

## 20 B. Results and Discussion

Combinations of inhibitors of HIV-1 attachment and gp41 fusion intermediates were first tested for the ability to inhibit HIV-1 env-mediated membrane fusion in the RET assay.  
25 This assay has proven to be a highly successful model of the HIV-1 entry process. In this assay, env-dependent coreceptor usage patterns and cellular tropisms of the parental viruses are accurately reproduced [19]. Indeed, the assay was instrumental in demonstrating that CCR5  
30 functions as a requisite fusion coreceptor and acts at the level of viral entry [54]. The fusion assay and infectious virus are similarly sensitive to inhibition by metal

chelators and agents that target the full complement of viral and cellular receptors [19,46,55].

5 Dose-response curves were obtained for the agents used individually and in combination in both assays. Data were analyzed using the median effect principle [52,53]. The concentrations of single-agents or their mixtures required to produce a given effect were quantitatively compared in a term known as the Combination Index (CI). CI > 1 indicates 10 antagonism, CI = 1 indicates a purely additive effect, and CI < 1 indicates a synergistic effect wherein the presence of one agent enhances the effect of another.

15 Combinations of CD4-IgG2 and T-20 were observed to be potentially synergistic in inhibiting env-mediated membrane fusion. Figure 1 illustrates representative dose-response curves obtained in the membrane fusion assay for CD4-IgG2, T-20, and combinations of the two. The curve for the combination is highly displaced towards lower inhibitor 20 concentrations and provides qualitative evidence that CD4-IgG2 and T-20 act in a synergistic manner.

To quantitatively calculate the degree of synergy observed between CD4-IgG2 and T-20, we analyzed the dose-response 25 curves according to the Combination Index method [52,53]. The analysis included data obtained at 25:1, 5:1, and 1:1 CD4-IgG2:T-20 mass ratios. At the 25:1 mass ratio, both high (0-250 µg/ml CD4-IgG2 and 0-10 µg/ml T-20) and low (0-50 µg/ml CD4-IgG2 and 0-2 µg/ml T-20) concentration ranges 30 were evaluated. As indicated in Figure 2, potent synergies were observed over these broad ranges of inhibitor ratios and concentrations, with CI values as low as 0.20 under

optimal conditions. This degree of synergy is remarkable since CI values of 0.2 are rarely observed for combinations involving anti-HIV-1 antibodies [41-44], reverse transcriptase inhibitors [56], or protease inhibitors [57].

5 The observed synergies indicate that HIV-1 attachment and formation of gp41 fusion intermediates are inter-dependent steps. One possibility is that attachment inhibitors, when used at suboptimal concentrations, may slow but not abrogate the binding of gp120 to CD4. In this case, gp41 fusion  
10 intermediates may be formed and persist on the virus (or infected cell) for longer periods of time at levels below that required for membrane fusion and thus provide better targets for inhibitory agents.

15 The observed synergies translate into significant reductions in the amounts of CD4-IgG2 and T-20 needed for inhibition. These reductions are illustrated in Figure 3 for CD4-IgG2 and T-20 used in a 25:1 mass ratio. By way of example, inhibition of viral entry by 95% requires 0.21 µg/ml of T-20  
20 used alone, 19 µg/ml of CD4-IgG2 used alone and 1.14 µg/ml of a combination containing 0.044 µg/ml of T-20 and 1.1 µg/ml of CD4-IgG2. The combination reduces the respective doses of T-20 and CD4-IgG2 by 5- and 17-fold, respectively. Still greater dose reductions are observed at higher levels  
25 of inhibition.

#### Second Series of Experiments

HIV-1 entry proceeds via a cascade of at least three sequential events: (1) the attachment of the HIV-1 surface  
30 glycoprotein gp120 to CD4, which is the primary cellular receptor for HIV-1, (2) the interaction of the gp120-CD4 complex with fusogenic coreceptors such as CCR5 and CXCR4,

and (3) membrane fusion mediated by the HIV-1 transmembrane glycoprotein gp41. PRO 542 (CD4-IgG2) is an antibody-like molecule that binds to gp120 and thereby inhibits attachment of the virus to host cells via CD4. PRO 140 (PA14) and PA12 are monoclonal antibodies to CCR5 that block its function as an HIV-1 coreceptor. Lastly, T-20 is a 36-mer peptide derived from the highly conserved C-terminal ectodomain of gp41. T-20 blocks gp41-mediated membrane fusion events. PRO 542 is thus an attachment inhibitor that blocks the first step of HIV-1 entry; PRO 140 and PA12 are both CCR5 coreceptor inhibitors that block the second step; and T-20 is a fusion inhibitor that blocks the third step. Attachment, coreceptor and fusion inhibitors are all members of a broad category of antiviral agents collectively know as HIV-1 entry inhibitors. CCR5 coreceptor inhibitors and CXCR4 coreceptor inhibitors constitute two distinct subclasses of coreceptor inhibitors.

When used individually, each of these compounds inhibit HIV-1 infection in vitro. PRO 542 and T-20 have also both demonstrated significant antiviral activity when used individually in human clinical trials, providing clinical proof-of-concept for inhibitors of HIV-1 entry (1,2).

The multi-step, inter-dependent nature of HIV-1 entry suggests that combinations of entry inhibitors may act in a non-additive or cooperative manner that either enhances (synergizes) or diminishes (antagonizes) the antiviral effect. Significant synergies have been observed for certain 2-way combinations of entry inhibitors, including attachment inhibitors used with CCR5 coreceptor inhibitors, attachment inhibitors used with fusion inhibitors, CCR5 coreceptor

inhibitors used with other CCR5 coreceptor inhibitors, and CXCR4 coreceptor inhibitors used with fusion inhibitors (3,4).

5 However, whereas synergies are observed with certain members of a given class of inhibitor, purely additive or even antagonistic effects are seen when other members of the same class are used (3), highlighting the complexity of the HIV-1 entry process and the difficulty of predicting synergistic combinations. No prior study has examined either 2-way  
10 combinations of CCR5 coreceptor inhibitors and fusion inhibitors or triple or higher combinations that include members of all three classes of HIV-1 entry inhibitors. We have discovered that synergistic inhibition of HIV-1 can be obtained using the CCR5 coreceptor inhibitor PRO 140 in combination with the fusion inhibitor T-20. See Figure 4D. In addition, remarkable synergies are observed using a triple combination containing an attachment inhibitor (PRO 542), a CCR5 coreceptor inhibitor (either PRO 140 or PA12)  
15 and a fusion inhibitor (T-20). See Figures 4A-C and Figure 5. The synergies observed with the triple combination are surprisingly potent and translate into dose reductions ranging to 260-fold.  
20

#### 25 REFERENCES FOR FIRST SERIES OF EXPERIMENTS

1. Arthos J, Deen KC, Chaikin MA et al. Identification of the residues in human CD4 critical for the binding of HIV. Cell 1989; 57:469-481.
  2. Clapham PR., Weber JN., Whitby D. et al. Soluble CD4 blocks the infectivity of diverse strains of HIV and SIV for T cells and monocytes but not for brain and muscle cells. Nature 1989; 337:368-370.
- 30

3. Deen KC., McDougal JS., Inacker R. et al. A soluble form of CD4 (T4) protein inhibits AIDS virus infection. *Nature* 1988; 331:82-84.
- 5 4. Capon DJ, Chamow SM, Mordenti J et al. Designing CD4 immunoadhesins for AIDS therapy. *Nature* 1989; 337:525-531.
- 10 5. Allaway GP, Davis-Bruno KL, Beaudry GA et al. Expression and characterization of CD4-IgG2, a novel heterotetramer which neutralizes primary HIV-1 isolates. *AIDS Research and Human Retroviruses* 1995; 11:533-539.
- 15 6. Allaway GP, Ryder AM, Beaudry GA, Maddon PJ. Synergistic inhibition of HIV-1 envelope-mediated cell fusion by CD4-based molecules in combination with antibodies to gp120 or gp41. *AIDS Research & Human Retroviruses* 1993; 9:581-587.
- 20 7. Vita C, Drakopoulou E, Vizzavona J et al. Rational engineering of a miniprotein that reproduces the core of the CD4 site interacting with HIV-1 envelope glycoprotein. *Proc Natl Acad Sci U S A* 1999; 96:13091-13096.
- 25 8. Schacker T., Coombs RW., Collier AC. et al. The effects of high-dose recombinant soluble CD4 on human immunodeficiency virus type 1 viremia. *Journal of Infectious Diseases* 1994; 169:37-40.
- 30 9. Schacker T, Collier AC, Coombs R et al. Phase I study of high-dose, intravenous rsCD4 in subjects with advanced HIV-1 infection. *J Acquir Immune Defic Syndr Hum Retrovirol* 1995; 9:145-152.
10. Collier AC, Coombs RW, Katzenstein D et al. Safety, pharmacokinetics, and antiviral response of CD4-immunoglobulin G by intravenous bolus in AIDS and AIDS-

related complex. J Acquir Immune Defic Syndr Hum Retrovirol 1995; 10:150-156.

11. Trkola A., Pomales AP., Yuan H. et al. Cross-clade neutralization of primary isolates of human immunodeficiency virus type 1 by human monoclonal antibodies and tetrameric CD4-IgG2. Journal of Virology 1995; 69:6609-6617.
12. Gauduin M-C., Allaway GP., Maddon PJ., Barbas CF3, Burton DR, Koup RA. Effective ex vivo neutralization of plasma HIV-1 by recombinant immunoglobulin molecules. Journal of Virology 1996; 70:2586-2592.
13. Gauduin M-C., Allaway GP, Olson WC, Weir R., Maddon PJ, Koup RA. CD4-immunoglobulin G2 protects Hu-PBL-SCID mice against challenge by primary human immunodeficiency virus type 1 isolates. Journal of Virology 1998; 72:3475-3478.
14. Trkola A, Ketas T, KewalRamani VN et al. Neutralization sensitivity of human immunodeficiency virus type 1 primary isolates to antibodies and CD4-based reagents is independent of coreceptor usage. J Virol 1998; 72:1876-1885.
15. Fouts TR, Binley JM, Trkola A, Robinson JE, Moore JP. Neutralization of the human immunodeficiency virus type 1 primary isolate JR-FL by human monoclonal antibodies correlates with antibody binding to the oligomeric form of the envelope glycoprotein complex. Journal of Virology 1997; 71:2779-2785.
16. Jacobson J, Lowy I, Trkola A et al. Results of a Rhase I Trial of Single-Dose PRO 542, a Novel Inhibitor of HIV Entry. Abstracts of the 39th Interscience Conference on Antimicrobial Agents and Chemotherapy 1999; 14.

17. Burton DR, Pyati J, Koduri R et al. Efficient neutralization of primary isolates of HIV-1 by a recombinant human monoclonal antibody. *Science* 1994; 266:1024-1027.
- 5 18. Posner MR., Cavacini LA., Emes CL., Power J., Byrn R. Neutralization of HIV-1 by F105, a human monoclonal antibody to the CD4 binding site of gp120. *Journal of Acquired Immune Deficiency Syndromes* 1993; 6:7-14.
- 10 19. Litwin V, Nagashima KA, Ryder AM et al. Human immunodeficiency virus type 1 membrane fusion mediated by a laboratory-adapted strain and a primary isolate analyzed by resonance energy transfer. *Journal of Virology* 1996; 70:6437-6441.
- 15 20. Pognard P, Peng T, Sabbe R, Newman W, Mosier DE, Burton DR. Blocking of HIV-1 Co-receptor CCR5 in the hu-PBL-SCID Mouse Leads to a Co-receptor Switch. 6th Conference on Retroviruses and Opportunistic Infections 1999;
- 20 21. Cushman M, Wang PL, Chang SH et al. Preparation and anti-HIV activities of aurointricarboxylic acid fractions and analogues: direct correlation of antiviral potency with molecular weight. *J Med Chem* 1991; 34:329-337.
- 25 22. Mohan P, Schols D, Baba M, De Clercq E. Sulfonic acid polymers as a new class of human immunodeficiency virus inhibitors. *Antiviral Res* 1992; 18:139-150.
- 30 23. Schols D, Pauwels R, Desmyter J, De Clercq E. Dextran sulfate and other polyanionic anti-HIV compounds specifically interact with the viral gp120 glycoprotein expressed by T-cells persistently infected with HIV-1. *Virology* 1990; 175:556-561.
24. Schols D, Wutzler P, Klocking R, Helbig B, De Clercq E.



Selective inhibitory activity of polyhydroxycarboxylates derived from phenolic compounds against human immunodeficiency virus replication. *J Acquir Immune Defic Syndr* 1991; 4:677-685.

25. Weissenhorn W, Dessen A, Harrison SC, Skehel JJ, Wiley DC. Atomic structure of the ectodomain from HIV-1 gp41. *Nature* 1997; 387:426-430.
26. Chan DC, Fass D, Berger JM, Kim PS. Core Structure of gp41 from the HIV Envelope Glycoprotein. *Cell* 1997; 89:263-273.
27. Ji H, Shu W, Burling FT, Jiang S, Lu M. Inhibition of human immunodeficiency virus type 1 infectivity by the gp41 core: role of a conserved hydrophobic cavity in membrane fusion. *Journal of Virology* 1999; 73:8578-8586.
28. Jiang S, Lin K, Strick N, Neurath AR. HIV-1 inhibition by a peptide. *Nature* 1993; 365:113.
29. Wild C, Greenwell T, Matthews T. A synthetic peptide from HIV-1 gp41 is a potent inhibitor of virus-mediated cell-cell fusion. *AIDS Res Hum Retroviruses* 1993; 9:1051-1053.
30. Wild C, Greenwell T, Shugars D, Rimsky-Clarke L, Matthews T. The inhibitory activity of an HIV type 1 peptide correlates with its ability to interact with a leucine zipper structure. *AIDS Res Hum Retroviruses* 1995; 11:323-325.
31. Wild C, Oas T, McDanal C, Bolognesi D, Matthews T. A synthetic peptide inhibitor of human immunodeficiency virus replication: correlation between solution structure and viral inhibition. *Proc Natl Acad Sci U S A* 1992; 89:10537-10541.
32. Wild CT, Shugars DC, Greenwell TK, McDanal CB, Matthews

TJ. Peptides corresponding to a predictive alpha-helical domain of human immunodeficiency virus type 1 gp41 are potent inhibitors of virus infection. *Proc Natl Acad Sci U S A* 1994; 91:9770-9774.

- 5 33. Chan DC, Chutkowski CT, Kim PS. Evidence that a prominent cavity in the coiled coil of HIV type 1 gp41 is an attractive drug target. *Proc Natl Acad Sci U S A* 1998; 95:15613-15617.
- 10 34. Ferrer M, Kapoor TM, Strassmaier T et al. Selection of gp41-mediated HIV-1 cell entry inhibitors from biased combinatorial libraries of non-natural binding elements. *Nat Struct Biol* 1999; 6:953-960.
- 15 35. Eckert DM, Malashkevich VN, Hong LH, Carr PA, Kim PS. Inhibiting HIV-1 entry: discovery of D-peptide inhibitors that target the gp41 coiled-coil pocket. *Cell* 1999; 99:103-115.
- 20 36. Kilby JM, Hopkins S, Venetta TM et al. Potent suppression of HIV-1 replication in humans by T-20, a peptide inhibitor of gp41-mediated virus entry. *Nat Med* 1998; 4:1302-1307.
37. LaCasse RA, Follis KE, Trahey M, Scarborough JD, Littman DR, Nunberg JH. Fusion-competent vaccines: broad neutralization of primary isolates of HIV. *Science* 1999; 283:357-362.
- 25 38. Neurath AR, Strick N, Lin K, Jiang S. Multifaceted consequences of anti-gp41 monoclonal antibody 2F5 binding to HIV type 1 virions. *AIDS Res Hum Retroviruses* 1995; 11:687-696.
- 30 39. Thali M, Furman C, Wahren B et al. Cooperativity of neutralizing antibodies directed against the V3 and CD4 binding regions of the human immunodeficiency virus gp120 envelope glycoprotein. *J Acquir Immune Defic*

Syndr 1992; 5:591-599.

40. Tilley SA, Honnen WJ, Racho ME, Chou TC, Pinter A. Synergistic neutralization of HIV-1 by human monoclonal antibodies against the V3 loop and the CD4-binding site of gp120. AIDS Res Hum Retroviruses 1992; 8:461-467.
41. Laal S, Burda S, Gorny MK, Karwowska S, Buchbinder A, Zolla-Pazner S. Synergistic neutralization of human immunodeficiency virus type 1 by combinations of human monoclonal antibodies. Journal of Virology 1994; 68:4001-4008.
42. Vijh-Warrier S, Pinter A, Honnen WJ, Tilley SA. Synergistic neutralization of human immunodeficiency virus type 1 by a chimpanzee monoclonal antibody against the V2 domain of gp120 in combination with monoclonal antibodies against the V3 loop and the CD4-binding site. Journal of Virology 1996; 70:4466-4473.
43. Li A, Baba TW, Sodroski J et al. Synergistic neutralization of a chimeric SIV/HIV type 1 virus with combinations of human anti-HIV type 1 envelope monoclonal antibodies or hyperimmune globulins. AIDS Res Hum Retroviruses 1997; 13:647-656.
44. Li A, Katinger H, Posner MR et al. Synergistic neutralization of simian-human immunodeficiency virus SHIV- vpu+ by triple and quadruple combinations of human monoclonal antibodies and high-titer anti-human immunodeficiency virus type 1 immunoglobulins. Journal of Virology 1998; 72:3235-3240.
45. Burkly L, Mulrey N, Blumenthal R, Dimitrov DS. Synergistic inhibition of human immunodeficiency virus type 1 envelope glycoprotein-mediated cell fusion and infection by an antibody to CD4 domain 2 in combination with anti-gp120 antibodies. Journal of Virology 1995;

69:4267-4273.

46. Olson WC, Rabut GE, Nagashima KA et al. Differential inhibition of human immunodeficiency virus type 1 fusion, gp120 binding, and CC-chemokine activity by monoclonal antibodies to CCR5. *J Virol* 1999; 73:4145-4155.
47. O'Brien WA., Koyanagi Y., Namazie A. et al. HIV-1 tropism for mononuclear phagocytes can be determined by regions of gp120 outside the CD4-binding domain. *Nature* 1990; 348:69-73.
48. Trkola A, Matthews J, Gordon C, Ketas T, Moore JP. A cell line-based neutralization assay for primary human immunodeficiency virus type 1 isolates that use either the CCR5 or the CXCR4 coreceptor. *J Virol* 1999; 73:8966-8974.
49. Fouts TR, Trkola A, Fung MS, Moore JP. Interactions of polyclonal and monoclonal anti-glycoprotein 120 antibodies with oligomeric glycoprotein 120-glycoprotein 41 complexes of a primary HIV type 1 isolate: relationship to neutralization. *AIDS Res Hum Retroviruses* 1998; 14:591-597.
50. Dreyer K, Kallas EG, Planelles V, Montefiori D, McDermott MP, Hasan MS. Primary isolate neutralization by HIV type 1-infected patient sera in the era of highly active antiretroviral therapy. *AIDS Research and Human Retroviruses* 1999; 15:1563-1571.
51. Allaway GP, Litwin VM, Maddon PJ. Progenics Pharmaceuticals, Inc. Methods for using resonance energy transfer-based assay of HIV-1 envelope glycoprotein-mediated membrane fusion, and kits for practicing same. International Filing Date June 7, 1996. International Patent Application No.

PCT/US96/09894. 1996;

52. Chou TC. The median effect principle and the combination index for quantitation of synergism and antagonism. *Synergism and Antagonism in Chemotherapy* 1991; 61-102.
53. Chou TC, Talalay P. Quantitative analysis of dose-effect relationships: the combined effects of multiple drugs or enzyme inhibitors. *Advances in Enzyme Regulation* 1984; 22:27-55.
54. Dragic T., Litwin V., Allaway GP. et al. HIV-1 entry into CD4+ cells is mediated by the chemokine receptor CC-CKR-5. *Nature* 1996; 381:667.
55. Donzella GA, Schols D, Lin SW et al. AMD3100, a small molecule inhibitor of HIV-1 entry via the CXCR4 co-receptor. *Nature Medicine* 1998; 4:72-77.
56. Johnson VA, Merrill DP, Videler JA et al. Two-drug combinations of zidovudine, didanosine, and recombinant interferon-alpha A inhibit replication of zidovudine-resistant human immunodeficiency virus type 1 synergistically in vitro. *Journal of Infectious Diseases* 1991; 164:646-655.
57. Merrill DP, Manion DJ, Chou TC, Hirsch MS. Antagonism between human immunodeficiency virus type 1 protease inhibitors indinavir and saquinavir in vitro. *Journal of Infectious Diseases* 1997; 176:265-268.
58. United States Patent No. 4,816,567, issued March 28, 1989 to Cabilly et al.
59. United States Patent No. 5,225,539, issued July 6, 1993 to Gregory Winter.
60. United States Patent No. 5,585,089, issued December 17, 1996 to Queen et al.
61. United States Patent No. 5,693,761, issued December 2,

1997 to Queen et al.

62. PCT International Application No. PCT/US89/05857, filed December 28, 1989, published July 26, 1990, WO 90/07861.

5 63. Jacobson, J.M. et al. Single-dose safety, pharmacology and antiviral activity of the human immunodeficiency virus (HIV) type 1 entry inhibitor PRO 542 in HIV-infected adults. J. Infect. Dis 182:326-329.

10 64. Kilby, J.M. et al. 1998 Potent suppression of HIV-1 replication in humans by T-20, a peptide inhibitor of gp-41 mediated virus entry. Nat. Med 4:1302-1307.

15 65. Olson. W.C. et al. 1999. Differential inhibition of human immunodeficiency virus type 1 fusion, gp120 binding, and CC-chemokine activity by monoclonal antibodies to CCR5. J. Virol 73:4145-4155.

66. Tremblay, C. et al. 2000. Strong in vitro synergy observed between the fusion inhibitor T-20 and a CXCR4 blocker AMD-3100. 7<sup>th</sup> Conference on Retroviruses and Opportunistic Infections, San Francisco.

20 67. Litwin, V. et al 1996, J. Virol 70:6437-6441.

SECOND SERIES OF EXPERIMENTS

Infection of cells by human immunodeficiency virus type 1 (HIV-1) is mediated by the viral envelope (env) glycoproteins gp120 and gp41, which are expressed as a noncovalent, oligomeric complex on the surface of virus and virally infected cells. HIV-1 entry into target cells proceeds at the cell surface through a cascade of events that include (1) binding of the viral surface glycoprotein gp120 to cell surface CD4, which is the primary receptor for HIV-1, (2) env binding to fusion coreceptors such as CCR5 and CXCR4, and (3) multiple conformational changes in gp41. During fusion, gp41 adopts transient conformations that include a prehairpin fusion intermediate that ultimately folds into a conformation capable of mediating fusion. These events culminate in fusion of the viral and cellular membranes and the subsequent introduction of the viral genome into the target cell. A similar sequence of molecular events is required for infection to spread via fusion of infected and uninfected cells. Each stage of the viral entry process can be targeted for therapeutic intervention.

HIV-1 attachment can be inhibited both by agents that bind the viral envelope glycoproteins and by agents that bind human CD4. Notably, HIV-1 attachment can be inhibited by compounds that incorporate the gp120-binding domains of human CD4 and molecular mimics thereof [1-7]. Because this interaction between gp120 and CD4 is essential for virus infection, CD4-based molecules have the potential to target most if not all strains of HIV-1. In addition, viruses have limited ability to develop resistance to such molecules.

The determinants for gp120 binding map to the first extracellular domain (D1) on CD4 [1], and the amino acids critical for binding center on a loop comprising amino acids 36-47. Potent HIV-1 inhibitory activity has been reproduced in a 27-amino acid peptide that mimics this loop and surrounding structures [7].

A number of recombinant CD4-based molecules have been developed and tested for clinical activity in man. The first of these contained the four extracellular domains (D1-D4) of CD4 but lacked the transmembrane and intracellular regions. This molecule, termed soluble CD4 (sCD4), demonstrated excellent tolerability when administered to humans at doses ranging to 10 mg/kg [8,9]. Transient reductions in plasma levels of infectious HIV-1 were observed in certain patients treated with sCD4. The short half-life of sCD4 in humans (45 minutes following intravenous administration) was identified as one obstacle to using this agent for chronic therapy.

Second-generation CD4-based proteins were developed with increased serum half-life. These CD4-immunoglobulin fusion proteins comprised the D1D2 domains of CD4 genetically fused to the hinge CH2 and CH3 regions of human IgG molecules. These divalent proteins derive HIV-1 neutralizing capacity from their CD4 domains and Fc effector functions from the IgG molecule. A CD4-IgG1 fusion protein was shown to have excellent tolerability and improved pharmacokinetics in Phase I clinical testing [10]. The antiviral evaluations were inconclusive.

More recently, a third-generation tetravalent CD4-IgG2



fusion protein was developed that comprises the D1D2 domains of CD4 genetically fused to the heavy and light chain constant regions of human IgG2. This agent binds the HIV-1 envelope glycoprotein gp120 with nanomolar affinity [5] and may inhibit virus attachment both by receptor blockade and by detaching gp120 from the virion surface, thereby irreversibly inactivating the virus. In standard PBMC-based neutralization assays, CD4-IgG2 neutralized primary HIV-1 isolates derived from all major subtypes and outlier groups. The CD4-IgG2 concentrations required to achieve a 90% reduction in viral infectivity, the in vitro IC90, were approximately 15-20 µg/ml [11], concentrations that are readily achievable in vivo. CD4-IgG2 was similarly effective in neutralizing HIV-1 obtained directly from the plasma of seropositive donors in an ex vivo assay, indicating that this agent is active against the diverse viral quasiespecies that are encountered clinically [12]. CD4-IgG2 also provided protection against infection by primary isolates in the hu-PBL-SCID mouse model of HIV-1 infection [13]. Recent analyses have demonstrated that CD4-IgG2's ability to neutralize primary viruses is independent of their coreceptor usage [14].

Compared with mono- or divalent CD4-based proteins, CD4-IgG2 has consistently demonstrated as much as 100-fold greater potency at inhibiting primary HIV-1 isolates [5,12,14,15]. The heightened potency may derive from CD4-IgG2's ability to bind virions with increased valency/avidity and its steric juxtaposition of two gp120 binding sites on each Fab-like arm of the immunoglobulin molecule. The larger Fab-like arms of CD4-IgG2 are also more likely to span HIV-1 envelope spikes on the virion. In a variety of preclinical models,

CD4-IgG2's anti-HIV-1 activity has been shown to compare favorably with those of the rare human monoclonal antibodies that broadly and potently neutralize primary HIV-1 isolates [5,11,14,15]. In addition, CD4-IgG2 therapy is in principle less susceptible to the development of drug-resistant viruses than therapies employing anti-env monoclonal antibodies or portions of the highly mutable HIV-1 envelope glycoproteins. These properties suggest that CD4-IgG2 may have clinical utility as an agent that neutralizes cell-free virus before it has the opportunity to establish new rounds of infection. In addition to treatment, CD4-IgG2 may have utility in preventing infection resulting from occupational, perinatal or other exposure to HIV-1.

In Phase I clinical testing, single-dose CD4-IgG2 demonstrated excellent pharmacology and tolerability. In addition, measurable antiviral activity was observed by each of two measures. First, a statistically significant acute reduction in plasma HIV RNA was observed following administration of a single 10 mg/kg dose. In addition, sustained reductions in plasma levels of infectious HIV were observed in each of two patients tested. Taken together, these observations indicate that CD4-IgG2 possesses antiviral activity in humans [16].

In addition to CD4-based proteins and molecular mimics thereof, HIV-1 attachment can also be inhibited by antibodies and nonpeptidyl molecules. Known inhibitors include (1) anti-env antibodies such as IgG1b12 and F105 [17,18], (2) anti-CD4 antibodies such as OKT4A, Leu 3a, and humanized versions thereof [19,20], and (3) nonpeptidyl agents that target either gp120 or CD4 [21], [22-24]. The

latter group of compounds includes aurintricarboxylic acids, polyhydroxycarboxylates, sulfonic acid polymers, and dextran sulfates.

5 Several agents have been identified that block HIV-1 infection by targeting gp41 fusion intermediates. These inhibitors may interact with the fusion intermediates and prevent them from folding into final fusogenic conformations. The first such agents to be identified  
10 comprised synthetic or recombinant peptides corresponding to portions of the gp41 ectodomain predicted to form hydrophobic alpha helices. One such region is present in both the amino and carboxy segments of the extracellular portion of gp41, and recent crystallographic evidence  
15 suggests that these regions interact in the presumed fusogenic conformation of gp41 [25,26]. HIV-1 infection can be inhibited by agents that bind to either N- or C-terminal gp41 epitopes that are exposed during fusion. These agents include the gp41-based peptides T-20 (formerly known as DP178), T-1249, DP107, N34, C28, and various fusion proteins  
20 and analogues thereof [27-33]. Other studies have identified inhibitors that comprise non-natural D-peptides and nonpeptidyl moieties [34,35]. Clinical proof-of-concept for this class of inhibitors has been provided by T-20, which  
25 reduced plasma HIV RNA levels by as much as 2 logs in Phase I/II human clinical testing [36]. The broad antiviral activity demonstrated for this class of inhibitors reflects the high degree of gp41 sequence conservation amongst diverse strains of HIV-1.

30 Recent studies [37] have demonstrated the possibility of raising antibodies against HIV-1 fusion intermediates. This

work employed "fusion-competent" HIV vaccine immunogens that capture transient fusion intermediates formed upon interaction of gp120/gp41 with CD4 and fusion coreceptors. The immunogens used in these studies were formalin-fixed cocultures of cells that express HIV-1 gp120/gp41 and cells that express human CD4 and CCR5 but not CXCR4. The antibodies elicited by the vaccines demonstrated unprecedented breadth and potency in inhibiting primary HIV-1 isolates regardless of their coreceptor usage, indicating that the antibodies were raised against structures such as gp41 fusion intermediates that are highly conserved and transiently exposed during HIV-1 entry. This class of antibodies does not include the anti-gp41 monoclonal antibody known as 2F5, which interacts with an epitope that is constitutively presented on virus particles prior to fusion [38].

Previously, synergistic inhibition of HIV-1 entry has been demonstrated using certain anti-env antibodies used in combination with other anti-env antibodies [39-44], anti-CD4 antibodies [45], or CD4-based proteins [6]. Similarly, synergies have been observed using anti-CCR5 antibodies used in combination with other anti-CCR5 antibodies, CC-chemokines, or CD4-based proteins [46]. However, no prior studies have examined the potential synergistic effects of combining inhibitors of gp41 fusion intermediates with inhibitors of other stages of HIV-1 entry. In particular, no studies have examined combinations of inhibitors of gp41 fusion intermediates and HIV-1 attachment.

#### A. Materials and Methods

1) Reagents

Purified recombinant CD4-IgG2 protein was produced by Progenics Pharmaceuticals, Inc. from plasmids CD4-IgG2-HC-pRcCMV and CD4-kLC-pRcCMV (ATCC Accession Nos. 75193 and 75194, respectively) as described [5]. HeLa-env cells were prepared by transfecting HeLa cells (ATCC Catalog # CCL-2) with HIV-1 gp120/gp41 env-expressing plasmid pMA243 as described [51]. PM1 cells are available from the National Institutes of Health AIDS Reagent Program (Catalog #3038). The T-20 peptide was synthesized using standard solid-phase Fmoc chemistry and purified and characterized as described [31,32].

2) Inhibition of HIV-1 env-mediated membrane fusion

HIV-1 envelope-mediated fusion between HeLa-Env<sub>JR-FL</sub> and PM1 cells was detected using a Resonance Energy Transfer (RET) assay. Equal numbers (2x10<sup>4</sup>) of fluorescein octadecyl ester (F18)-labeled envelope-expressing cells and octadecyl rhodamine (R18)-labeled PM1 cells were plated in 96-well plates in 15% fetal calf serum in phosphate buffered saline and incubated for 4h at 37 °C in the presence of varying concentrations of CD4-IgG2, T-20 or combinations thereof. Fluorescence RET was measured with a Cytofluor plate-reader (PerSeptive Biosystems) and % RET was determined as previously described [19].

3) Quantitative analysis of the synergistic, additive or antagonistic effects of combining the agents

HIV-1 inhibition data were analyzed according to the Combination Index method of Chou and Talay [52,53]. The data are modeled according to the median-effect principle,

which can be written

$$f = 1/[1 + (K/c)^m] \quad (1)$$

where  $f$  is the fraction affected/inhibited,  $c$  is concentration,  $K$  is the concentration of agent required to produce the median effect, and  $m$  is an empirical coefficient describing the shape of the dose-response curve. Equation (1) is a generalized form of the equations describing Michaelis-Menton enzyme kinetics, Langmuir adsorption isotherms, and Henderson-Hasselbalch ionization equilibria, for which  $m = 1$  in all cases. In the present case,  $K$  is equal to the  $IC_{50}$  value.  $K$  and  $m$  are determined by curve-fitting the dose-response curves.

After the best-fit parameters for  $K$  and  $m$  are obtained for the experimental agents and their combination, Equation (1) is rearranged to allow for calculation of  $c$  for a given  $f$ . The resulting table of values (e.g., Figure X) is used to calculate the Combination Index (CI) using the equation

$$CI = c_{1m}/c_1 + c_{2m}/c_2 + c_{1m}c_{2m}/c_1c_2 \quad (2)$$

where

$c_1$  = concentration of compound 1 when used alone  
 $c_2$  = concentration of compound 2 when used alone  
 $c_{1m}$  = concentration of compound 1 in the mixture

$C_{2m}$  = concentration of compound 2 in the mixture

All concentrations are those required to achieve a given degree of inhibition. Equation (2) is used when the molecules are mutually nonexclusive, i.e., have different sites of action. Since this is the likely scenario for inhibitors of HIV-1 attachment and gp41 fusion intermediates, Equation (2) was used for all Combination Index calculations. Mutually nonexclusive calculations provide a more conservative estimate of the degree of synergy that mutually exclusive calculations, for which the  $C_{1m}C_{2m}/C_1C_2$  term is dropped.  $CI < 1$  indicates synergy,  $CI = 1$  indicates purely additive effects, and  $CI > 1$  indicates antagonism. In general, CI values are most relevant at the higher levels of inhibition that are required to achieve a measurable clinical benefit.

## B. Results and Discussion

Combinations of inhibitors of HIV-1 attachment and gp41 fusion intermediates were first tested for the ability to inhibit HIV-1 env-mediated membrane fusion in the RET assay. This assay has proven to be a highly successful model of the HIV-1 entry process. In this assay, env-dependent coreceptor usage patterns and cellular tropisms of the parental viruses are accurately reproduced [19]. Indeed, the assay was instrumental in demonstrating that CCR5 functions as a requisite fusion coreceptor and acts at the level of viral entry [54]. The fusion assay and infectious virus are similarly sensitive to inhibition by metal chelators and agents that target the full complement of viral and cellular receptors [19,46,55].

Dose-response curves were obtained for the agents used individually and in combination in both assays. Data were analyzed using the median effect principle [52,53]. The concentrations of single-agents or their mixtures required to produce a given effect were quantitatively compared in a term known as the Combination Index (CI). CI > 1 indicates antagonism, CI = 1 indicates a purely additive effect, and CI < 1 indicates a synergistic effect wherein the presence of one agent enhances the effect of another.

Combinations of CD4-IgG2 and T-20 were observed to be potentially synergistic in inhibiting env-mediated membrane fusion. Figure 6 illustrates representative dose-response curves obtained in the membrane fusion assay for CD4-IgG2, T-20, and combinations of the two. The curve for the combination is highly displaced towards lower inhibitor concentrations and provides qualitative evidence that CD4-IgG2 and T-20 act in a synergistic manner.

To quantitatively calculate the degree of synergy observed between CD4-IgG2 and T-20, we analyzed the dose-response curves according to the Combination Index method [52,53]. The analysis included data obtained at 25:1, 5:1, and 1:1 CD4-IgG2:T-20 mass ratios. At the 25:1 mass ratio, both high (0-250 µg/ml CD4-IgG2 and 0-10 µg/ml T-20) and low (0-50 µg/ml CD4-IgG2 and 0-2 µg/ml T-20) concentration ranges were evaluated. As indicated in Figure 7, potent synergies were observed over these broad ranges of inhibitor ratios and concentrations, with CI values as low as 0.20 under optimal conditions. This degree of synergy is remarkable since CI values of 0.2 are rarely observed for combinations involving anti-HIV-1 antibodies [41-44], reverse



transcriptase inhibitors [56], or protease inhibitors [57]. The observed synergies indicate that HIV-1 attachment and formation of gp41 fusion intermediates are inter-dependent steps. One possibility is that attachment inhibitors, when  
5 used at suboptimal concentrations, may slow but not abrogate the binding of gp120 to CD4. In this case, gp41 fusion intermediates may be formed and persist on the virus (or infected cell) for longer periods of time at levels below that required for membrane fusion and thus provide better  
10 targets for inhibitory agents.

The observed synergies translate into significant reductions in the amounts of CD4-IgG2 and T-20 needed for inhibition. These reductions are illustrated in Figure 8 for CD4-IgG2  
15 and T-20 used in a 25:1 mass ratio. By way of example, inhibition of viral entry by 95% requires 0.21 µg/ml of T-20 used alone, 19 µg/ml of CD4-IgG2 used alone and 1.14 µg/ml of a combination containing 0.044 µg/ml of T-20 and 1.1 µg/ml of CD4-IgG2. The combination reduces the respective  
20 doses of T-20 and CD4-IgG2 by 5- and 17-fold, respectively. Still greater dose reductions are observed at higher levels of inhibition.

#### 25 REFERENCES FOR SECOND SERIES OF EXPERIMENTS

1. Arthos J, Deen KC, Chaikin MA et al. Identification of the residues in human CD4 critical for the binding of HIV. Cell 1989; 57:469-481.
- 30 2. Clapham PR., Weber JN., Whitby D. et al. Soluble CD4 blocks the infectivity of diverse strains of HIV and SIV for T cells and monocytes but not for brain and

muscle cells. Nature 1989; 337:368-370.

3. Deen KC., McDougal JS., Inacker R. et al. A soluble form of CD4 (T4) protein inhibits AIDS virus infection. Nature 1988; 331:82-84.
4. Capon DJ, Chamow SM, Mordenti J et al. Designing CD4 immunoadhesins for AIDS therapy. Nature 1989; 337:525-531.
5. Allaway GP, Davis-Bruno KL, Beaudry GA et al. Expression and characterization of CD4-IgG2, a novel heterotetramer which neutralizes primary HIV-1 isolates. AIDS Research and Human Retroviruses 1995; 11:533-539.
6. Allaway GP, Ryder AM, Beaudry GA, Maddon PJ. Synergistic inhibition of HIV-1 envelope-mediated cell fusion by CD4-based molecules in combination with antibodies to gp120 or gp41. AIDS Research & Human Retroviruses 1993; 9:581-587.
7. Vita C, Drakopoulou E, Vizzavona J et al. Rational engineering of a miniprotein that reproduces the core of the CD4 site interacting with HIV-1 envelope glycoprotein. Proc Natl Acad Sci U S A 1999; 96:13091-13096.
8. Schacker T., Coombs RW., Collier AC. et al. The effects of high-dose recombinant soluble CD4 on human immunodeficiency virus type 1 viremia. Journal of Infectious Diseases 1994; 169:37-40.

9. Schacker T, Collier AC, Coombs R et al. Phase I study of high-dose, intravenous rsCD4 in subjects with advanced HIV-1 infection. *J Acquir Immune Defic Syndr Hum Retrovirol* 1995; 9:145-152.
- 5 10. Collier AC, Coombs RW, Katzenstein D et al. Safety, pharmacokinetics, and antiviral response of CD4-immunoglobulin G by intravenous bolus in AIDS and AIDS-related complex. *J Acquir Immune Defic Syndr Hum Retrovirol* 1995; 10:150-156.
- 10 11. Trkola A., Pomales AP., Yuan H. et al. Cross-clade neutralization of primary isolates of human immunodeficiency virus type 1 by human monoclonal antibodies and tetrameric CD4-IgG2. *Journal of Virology* 1995; 69:6609-6617.
- 15 12. Gauduin M-C., Allaway GP., Maddon PJ., Barbas CF3, Burton DR, Koup RA. Effective ex vivo neutralization of plasma HIV-1 by recombinant immunoglobulin molecules. *Journal of Virology* 1996; 70:2586-2592.
- 20 13. Gauduin M-C., Allaway GP, Olson WC, Weir R., Maddon PJ, Koup RA. CD4-immunoglobulin G2 protects Hu-PBL-SCID mice against challenge by primary human immunodeficiency virus type 1 isolates. *Journal of Virology* 1998; 72:3475-3478.
- 25 14. Trkola A, Ketas T, KewalRamani VN et al. Neutralization sensitivity of human immunodeficiency virus type 1 primary isolates to antibodies and CD4-based reagents is independent of coreceptor usage. *J Virol* 1998;
- 30

72:1876-1885.

15. Fouts TR, Binley JM, Trkola A, Robinson JE, Moore JP.  
Neutralization of the human immunodeficiency virus type  
1 primary isolate JR-FL by human monoclonal antibodies  
correlates with antibody binding to the oligomeric form  
of the envelope glycoprotein complex. Journal of  
Virology 1997; 71:2779-2785.
16. Jacobson J, Lowy I, Trkola A et al. Results of a Rhase  
I Trial of Single-Dose PRO 542, a Novel Inhibitor of  
HIV Entry. Abstracts of the 39th Interscience  
Conference on Antimicrobial Agents and Chemotherapy  
1999; 14.
17. Burton DR, Pyati J, Koduri R et al. Efficient  
neutralization of primary isolates of HIV-1 by a  
recombinant human monoclonal antibody. Science 1994;  
266:1024-1027.
18. Posner MR., Cavacini LA., Emes CL., Power J., Byrn R.  
Neutralization of HIV-1 by F105, a human monoclonal  
antibody to the CD4 binding site of gp120. Journal of  
Acquired Immune Deficiency Syndromes 1993; 6:7-14.
19. Litwin V, Nagashima KA, Ryder AM et al. Human  
immunodeficiency virus type 1 membrane fusion mediated  
by a laboratory-adapted strain and a primary isolate  
analyzed by resonance energy transfer. Journal of  
Virology 1996; 70:6437-6441.
20. Poignard P, Peng T, Sabbe R, Newman W, Mosier DE,

Burton DR. Blocking of HIV-1 Co-receptor CCR5 in the hu-PBL-SCID Mouse Leads to a Co-receptor Switch. 6th Conference on Retroviruses and Opportunistic Infections 1999;

5

21. Cushman M, Wang PL, Chang SH et al. Preparation and anti-HIV activities of aurointricarboxylic acid fractions and analogues: direct correlation of antiviral potency with molecular weight. J Med Chem 1991; 34:329-337.

10

22. Mohan P, Schols D, Baba M, De Clercq E. Sulfonic acid polymers as a new class of human immunodeficiency virus inhibitors. Antiviral Res 1992; 18:139-150.

15

23. Schols D, Pauwels R, Desmyter J, De Clercq E. Dextran sulfate and other polyanionic anti-HIV compounds specifically interact with the viral gp120 glycoprotein expressed by T-cells persistently infected with HIV-1. Virology 1990; 175:556-561.

20

24. Schols D, Wutzler P, Klocking R, Helbig B, De Clercq E. Selective inhibitory activity of polyhydroxycarboxylates derived from phenolic compounds against human immunodeficiency virus replication. J Acquir Immune Defic Syndr 1991; 4:677-685.

25

25. Weissenhorn W, Dessen A, Harrison SC, Skehel JJ, Wiley DC. Atomic structure of the ectodomain from HIV-1 gp41. Nature 1997; 387:426-430.

30

26. Chan DC, Fass D, Berger JM, Kim PS. Core Structure of

gp41 from the HIV Envelope Glycoprotein. Cell 1997; 89:263-273.

- 5 27. Ji H, Shu W, Burling FT, Jiang S, Lu M. Inhibition of human immunodeficiency virus type 1 infectivity by the gp41 core: role of a conserved hydrophobic cavity in membrane fusion. Journal of Virology 1999; 73:8578-8586.
- 10 28. Jiang S, Lin K, Strick N, Neurath AR. HIV-1 inhibition by a peptide. Nature 1993; 365:113.
- 15 29. Wild C, Greenwell T, Matthews T. A synthetic peptide from HIV-1 gp41 is a potent inhibitor of virus-mediated cell-cell fusion. AIDS Res Hum Retroviruses 1993; 9:1051-1053.
- 20 30. Wild C, Greenwell T, Shugars D, Rimsky-Clarke L, Matthews T. The inhibitory activity of an HIV type 1 peptide correlates with its ability to interact with a leucine zipper structure. AIDS Res Hum Retroviruses 1995; 11:323-325.
- 25 31. Wild C, Oas T, McDanal C, Bolognesi D, Matthews T. A synthetic peptide inhibitor of human immunodeficiency virus replication: correlation between solution structure and viral inhibition. Proc Natl Acad Sci U S A 1992; 89:10537-10541.
- 30 32. Wild CT, Shugars DC, Greenwell TK, McDanal CB, Matthews TJ. Peptides corresponding to a predictive alpha-helical domain of human immunodeficiency virus type 1

gp41 are potent inhibitors of virus infection. Proc Natl Acad Sci U S A 1994; 91:9770-9774.

- 5 33. Chan DC, Chutkowski CT, Kim PS. Evidence that a prominent cavity in the coiled coil of HIV type 1 gp41 is an attractive drug target. Proc Natl Acad Sci U S A 1998; 95:15613-15617.
- 10 34. Ferrer M, Kapoor TM, Strassmaier T et al. Selection of gp41-mediated HIV-1 cell entry inhibitors from biased combinatorial libraries of non-natural binding elements. Nat Struct Biol 1999; 6:953-960.
- 15 35. Eckert DM, Malashkevich VN, Hong LH, Carr PA, Kim PS. Inhibiting HIV-1 entry: discovery of D-peptide inhibitors that target the gp41 coiled-coil pocket. Cell 1999; 99:103-115.
- 20 36. Kilby JM, Hopkins S, Venetta TM et al. Potent suppression of HIV-1 replication in humans by T-20, a peptide inhibitor of gp41-mediated virus entry. Nat Med 1998; 4:1302-1307.
- 25 37. LaCasse RA, Follis KE, Trahey M, Scarborough JD, Littman DR, Nunberg JH. Fusion-competent vaccines: broad neutralization of primary isolates of HIV. Science 1999; 283:357-362.
- 30 38. Neurath AR, Strick N, Lin K, Jiang S. Multifaceted consequences of anti-gp41 monoclonal antibody 2F5 binding to HIV type 1 virions. AIDS Res Hum Retroviruses 1995; 11:687-696.

39. Thali M, Furman C, Wahren B et al. Cooperativity of neutralizing antibodies directed against the V3 and CD4 binding regions of the human immunodeficiency virus gp120 envelope glycoprotein. *J Acquir Immune Defic Syndr* 1992; 5:591-599.
40. Tilley SA, Honnen WJ, Racho ME, Chou TC, Pinter A. Synergistic neutralization of HIV-1 by human monoclonal antibodies against the V3 loop and the CD4-binding site of gp120. *AIDS Res Hum Retroviruses* 1992; 8:461-467.
41. Laal S, Burda S, Gorny MK, Karwowska S, Buchbinder A, Zolla-Pazner S. Synergistic neutralization of human immunodeficiency virus type 1 by combinations of human monoclonal antibodies. *Journal of Virology* 1994; 68:4001-4008.
42. Vijh-Warrier S, Pinter A, Honnen WJ, Tilley SA. Synergistic neutralization of human immunodeficiency virus type 1 by a chimpanzee monoclonal antibody against the V2 domain of gp120 in combination with monoclonal antibodies against the V3 loop and the CD4-binding site. *Journal of Virology* 1996; 70:4466-4473.
43. Li A, Baba TW, Sodroski J et al. Synergistic neutralization of a chimeric SIV/HIV type 1 virus with combinations of human anti-HIV type 1 envelope monoclonal antibodies or hyperimmune globulins. *AIDS Res Hum Retroviruses* 1997; 13:647-656.
44. Li A, Katinger H, Posner MR et al. Synergistic neutralization of simian-human immunodeficiency virus



SHIV- vpu+ by triple and quadruple combinations of human monoclonal antibodies and high-titer anti-human immunodeficiency virus type 1 immunoglobulins. Journal of Virology 1998; 72:3235-3240.

- 5 45. Burkly L, Mulrey N, Blumenthal R, Dimitrov DS. Synergistic inhibition of human immunodeficiency virus type 1 envelope glycoprotein-mediated cell fusion and infection by an antibody to CD4 domain 2 in combination with anti-gp120 antibodies. Journal of Virology 1995; 69:4267-4273.
- 10 46. Olson WC, Rabut GE, Nagashima KA et al. Differential inhibition of human immunodeficiency virus type 1 fusion, gp120 binding, and CC-chemokine activity by monoclonal antibodies to CCR5. J Virol 1999; 73:4145-4155.
- 15 47. O'Brien WA., Koyanagi Y., Namazie A. et al. HIV-1 tropism for mononuclear phagocytes can be determined by regions of gp120 outside the CD4-binding domain. Nature 1990; 348:69-73.
- 20 48. Trkola A, Matthews J, Gordon C, Ketas T, Moore JP. A cell line-based neutralization assay for primary human immunodeficiency virus type 1 isolates that use either the CCR5 or the CXCR4 coreceptor. J Virol 1999; 73:8966-8974.
- 25 49. Fouts TR, Trkola A, Fung MS, Moore JP. Interactions of polyclonal and monoclonal anti-glycoprotein 120 antibodies with oligomeric glycoprotein 120-
- 30

glycoprotein 41 complexes of a primary HIV type 1 isolate: relationship to neutralization. AIDS Res Hum Retroviruses 1998; 14:591-597.

- 5 50. Dreyer K, Kallas EG, Planelles V, Montefiori D, McDermott MP, Hasan MS. Primary isolate neutralization by HIV type 1-infected patient sera in the era of highly active antiretroviral therapy. AIDS Research and Human Retroviruses 1999; 15:1563-1571.
- 10 51. Allaway GP, Litwin VM, Maddon PJ. Progenics Pharmaceuticals, Inc. Methods for using resonance energy transfer-based assay of HIV-1 envelope glycoprotein-mediated membrane fusion, and kits for practicing same. International Filing Date June 7, 15 1996. International Patent Application No. PCT/US96/09894. 1996;
- 20 52. Chou TC. The median effect principle and the combination index for quantitation of synergism and antagonism. Synergism and Antagonism in Chemotherapy 1991; 61-102.
- 25 53. Chou TC, Talalay P. Quantitative analysis of dose-effect relationships: the combined effects of multiple drugs or enzyme inhibitors. Advances in Enzyme Regulation 1984; 22:27-55.
- 30 54. Dragic T., Litwin V., Allaway GP. et al. HIV-1 entry into CD4+ cells is mediated by the chemokine receptor CC-CKR-5. Nature 1996; 381:667.

55. Donzella GA, Schols D, Lin SW et al. AMD3100, a small molecule inhibitor of HIV-1 entry via the CXCR4 co-receptor. *Nature Medicine* 1998; 4:72-77.

5 56. Johnson VA, Merrill DP, Videler JA et al. Two-drug combinations of zidovudine, didanosine, and recombinant interferon-alpha A inhibit replication of zidovudine-resistant human immunodeficiency virus type 1 synergistically in vitro. *Journal of Infectious Diseases* 1991; 164:646-655.

10 57. Merrill DP, Manion DJ, Chou TC, Hirsch MS. Antagonism between human immunodeficiency virus type 1 protease inhibitors indinavir and saquinavir in vitro. *Journal of Infectious Diseases* 1997; 176:265-268.

### THIRD SERIES OF EXPERIMENTS

HIV-1 entry proceeds via a cascade of events that afford promising targets for therapy. PRO 542 neutralizes HIV-1 by blocking its attachment to CD4, and T-20 blocks gp41-mediated fusion. Both drugs have shown promise in Phase I/II clinical trials. Here the drugs were tested individually and in combination in preclinical models of HIV-1 infection, and inhibition data were analyzed for cooperativity using the Combination Index method. Synergistic inhibition of virus-cell and cell-cell fusion was observed for phenotypically diverse viruses over a broad range of drug concentrations, often resulting in 10-fold or greater dose reductions in vitro. Additional mechanism-of-action studies probed the molecular basis of the synergies. The markedly enhanced activity observed for the PRO 542:T-20 combination indicates that the multi-step nature of HIV-1 entry leaves the virus particularly vulnerable to combinations of entry inhibitors. These findings provide a strong rationale for evaluating combinations of these agents for therapy in vivo.

Despite recent advances, present therapies for human immunodeficiency virus type 1 (HIV-1) infection are limited by their failure to eradicate HIV-1, the emergence of multi-drug resistant variants, and significant toxicities. Accordingly, there is an urgent need for new therapies that target additional stages of the HIV-1 replicative cycle, such as viral entry.

HIV-1 entry comprises three steps that provide promising targets for therapy: (1) the attachment of the HIV-1 surface glycoprotein gp120 to CD4, (2) the interaction of the gp120-

CD4 complex with a coreceptor, and (3) membrane fusion mediated by the HIV-1 transmembrane glycoprotein gp41. Attachment, coreceptor, and fusion inhibitors are broadly referred to as entry inhibitors and are currently in clinical development [1-4].

The attachment inhibitor PRO 542 (CD4-IgG2) is a tetravalent CD4-immunoglobulin fusion protein that potently neutralizes primary HIV-1 isolates [5]. In Phase I/II testing, PRO 542 has demonstrated excellent tolerability and pharmacology and has reduced viral loads as measured by plasma HIV RNA, plasma viremia, and cell-associated virus [1,2]. PRO 542 is currently in Phase II clinical testing.

The fusion inhibitor T-20 is a peptide derived from the C-terminal ectodomain of gp41. T-20 possesses broad-spectrum antiviral activity mediated by its ability to act upon transient gp41 fusion intermediates [6,7]. Although the precise structures of the fusion intermediates are not known, they are known as "pre-hairpin" intermediates based on the post-fusion conformation of gp41. T-20 mediated 1-2 log<sub>10</sub> reductions in HIV RNA when used as a single agent in Phase I/II trials and has been associated with prolonged viral suppression when used with FDA-approved antiretrovirals [3,4]. T-20 has entered Phase III clinical testing.

Combinations of antiretroviral medications are required for durable suppression of HIV-1 replication. PRO 542 and T-20 are attractive candidates for combination use because they are well-tolerated, "first-in-class" agents that target distinct stages of HIV-1 entry. Moreover, the multi-step,

interdependent nature of HIV-1 entry suggests that these drugs might act in a non-additive manner. In this study, we evaluated these agents individually and in combination in vitro and analyzed the results for cooperative effects. The PRO 542:T-20 combination potently and synergistically inhibited entry of phenotypically diverse HIV-1 isolates over a broad range of experimental conditions. Additional studies shed light on the molecular basis for the enhanced antiviral activity.

## **MATERIALS AND METHODS**

**Compounds** PRO 542 was expressed in Chinese hamster ovary cells and purified by column chromatography by Progenics [5]. T-20 was synthesized by solid-phase fluorenylmethoxycarbonyl chemistry, purified by reversed phase chromatography and analyzed for purity and size by HPLC and mass spectroscopy by Progenics. PRO 542 and T-20 were formulated in phosphate buffered saline and stored at -95°C.

**HIV-1 virus-cell fusion assays** NLuc<sup>env</sup> viruses were complemented in trans by the envelope glycoproteins (Env) from HIV-1<sub>JR-FL</sub> (R5) or HIV-1<sub>DH123</sub> (R5X4) [8]. HeLa-CD4<sup>+</sup>CCR5<sup>+</sup> cells were infected with chimeric reporter viruses containing 50-100 ng/ml of p24 in the presence or absence of drugs. Cells were washed and fed fresh drug-containing media at 2 h and drug-free media at 12 h. After 72 h, cell lysates were assayed for luciferase activity [9].

**HIV-1 cell-cell fusion assays** Cell-cell fusion mediated by the envelope glycoproteins of HIV-1<sub>JR-FL</sub> and HIV-1<sub>LAI</sub> was measured using a fluorescence resonance energy transfer

(RET) assay [10], which measures fusion between HeLa cells expressing HIV-1 envelope glycoproteins and CD4<sup>+</sup> target cells. The T cell lines PM1 and SupT1 were used as target cells in this study. PM1 endogenously express CCR5 and CXCR4. Cells are membrane-labeled with fluorescent dyes that possess overlapping excitation and emission spectra, such that RET occurs when the dyes are placed in the same membrane following fusion. The RET signal is directly related to the extent of membrane fusion.

**Quantitative analysis of drug interactions** Inhibition data from three independent assays were averaged and analyzed for cooperative effects using the Combination Index (CI) method [11]. In all analyses, PRO 542 and T-20 were assumed to act non-competitively, which leads to a more conservative estimate of synergy. CI values of <0.9 (or >1.1) were taken to represent meaningful synergy (or antagonism). Dose reductions were calculated as the ratio of drug concentrations required for inhibition when the drug is used alone or in combination [11].

## RESULTS

**Inhibition of HIV-1 virus-cell fusion** PRO 542, T-20 and 1:2 molar combinations thereof were used to inhibit HIV-1<sub>JR-FL</sub> and HIV-1<sub>DH123</sub> entry. For HIV-1<sub>JR-FL</sub> (Figure 9a), the concentration required for 90% inhibition (IC<sub>90</sub>) was 12 nM for PRO 542, 45 nM for T-20 and 4.1 nM for the combination (1.5 nM PRO 542 and 2.6 nM T-20). Favorable drug-drug interactions are evident from the fact that the IC<sub>90</sub> of the combination is substantially lower than that of either compound alone.

Combination Index analyses (Figure 10) demonstrated that potent PRO 542:T-20 synergy was observed for both HIV-1<sub>JR-FL</sub> and HIV-1<sub>DH123</sub>. Over the range of 50-95% inhibition, CI values ranged from 0.39-0.14 for HIV-1<sub>JR-FL</sub> and 1.1-0.36 for HIV-1<sub>DH123</sub>. Approximately 10-fold less PRO 542 and 20-fold less T-20 was needed to inhibit HIV-1<sub>JR-FL</sub> entry by 90-95%. Significant dose reductions were also observed for HIV-1<sub>DH123</sub> (Figure 10).

**Inhibition of HIV-1 Env-mediated cell-cell fusion** PRO 542, T-20 and 1:10 molar combinations thereof were used to inhibit HIV-1<sub>JR-FL</sub> Env-mediated cell-cell fusion in the RET assay (Figure 9b). IC<sub>90</sub> values were 11 nM for PRO 542, 22 nM for T-20 and 5.5 nM for the combination (0.55 nM PRO 542 and 4.9 nM T-20). CI values ranged from 0.34-0.27 over the range of 50-95% inhibition (Figure 10). Robust synergies were also observed using PRO 542:T-20 molar ratios of 1:2 and 1:50 and translated into dose reductions ranging to 50-fold (Figure 10).

PRO 542 and T-20 also synergistically inhibited HIV-1<sub>LAI</sub> (X4) Env-mediated fusion. At a 1:10 PRO 542:T-20 ratio, CI values ranged from 0.45-0.28 at 50-95% inhibition. The dose reductions ranged from 12-fold to 30-fold for PRO 542 and from 2.5-fold to 5.4-fold for T-20. Synergy was also observed when the SupT1 T cell line was used instead of FM1 (data not shown).

**Mechanistic studies of PRO 542:T-20 synergy** T-20 does not interact with Env in its pre-fusion conformation but rather targets transient gp41 structures [7]. PRO 542, on the other hand, neutralizes free virus and triggers Env



conformational changes that are required for entry [12]. PRO 542 could conceivably trigger formation of gp41 fusion intermediates, enabling T-20 to act on free virus. To evaluate this hypothesis, PRO 542 and T-20 were pre-incubated alone and in combination for 1 h at 37 °C with HeLa-Env cells prior to washing and the addition of PM1 cells (Figure 9c). Whereas PRO 542 demonstrated 6-fold lower but nonetheless significant potency, T-20 was essentially inactive in this setting. The potency of the PRO 542:T-20 mixture mirrored that of its PRO 542 content, indicating that T-20 was inactive in the mixture and suggesting that PRO 542 does not trigger formation of the pre-hairpin intermediate. This result also indicates that PRO 542:T-20 synergy does not reflect direct binding between the compounds. Neither drug demonstrated activity when pre-incubated with PM1 cells prior to washing (data not shown).

Further experiments explored the conditions required to form the pre-hairpin intermediate. HeLa-Env and PM1 cells were co-incubated for 2 h at 25 °C, a temperature that is not permissive for HIV-1 fusion [13]. Inhibitor was added, and the cells were warmed to 37 °C. Whereas PRO 542 was measurably less potent in blocking fusion under these conditions, T-20 was fully active (Figure 1d). Thus at 25 °C, HIV-1 fusion can proceed past gp120-CD4 attachment but is arrested at or before the formation of the pre-hairpin intermediate. Similar results were obtained when the cells were incubated 16 h at 25 °C prior to the addition of inhibitor (data not shown).

Lastly, HeLa-Env cells, PM1 cells, and inhibitor (PRO 542, T-20 or a 1:10 combination) were co-incubated for 2 h at 25

°C prior to washing and warming to 37 °C. Under these conditions, PRO 542 demonstrated ~12-fold lower but nonetheless significant activity; T-20 was essentially inactive (>250-fold increase in IC<sub>50</sub>); and the combination possessed activity consistent with its PRO 542 content (data not shown). Taken together, the results indicate that the pre-hairpin intermediate forms only when Env, CD4 and coreceptor interact at a fusion-permissive temperature.

## DISCUSSION

HIV-1 entry is a promising target for a new generation of antiretroviral therapies, and PRO 542 and T-20 are "first-in-class" investigational agents that block distinct stages of this highly cooperative process. Recognizing that combinations of entry inhibitors may emerge as a new paradigm for HIV-1 therapy, this study explored PRO 542:T-20 combinations in two preclinical models of HIV-1 infection. Potent synergy was observed for both virus-cell and cell-cell fusion, for phenotypically diverse virus isolates, and over a broad range of drug concentrations. In many instances, the synergy translated into 10-fold or greater dose reductions for PRO 542 and T-20 in vitro. Thus the multi-step nature of HIV-1 entry appears to leave the virus particularly vulnerable to cooperative inhibition. The findings provide a strong rationale for combination clinical trials designed to maximize the therapeutic potential of each compound.

If borne out in vivo, these findings could translate into a number of important clinical benefits. First, more potent therapies reduce the emergence of drug-resistant virus and thereby preserve a patient's therapeutic options. In

addition, by reducing the amount of PRO 542 and T-20 required for therapy, the synergy could enable simplified dosing regimens. Dose-sparing regimens are in general also toxicity-sparing, although this may be of less concern for PRO 542 and T-20, which have been well-tolerated in clinical testing to date.

For virus-cell fusion, larger dose reductions were seen for T-20 than for PRO 542, whereas the reverse was true for cell-cell fusion. The relative dose reductions reflect the complementary mechanisms of action of the two products: PRO 542 but not T-20 neutralizes cell-free virus, and T-20 is particularly effective in blocking cell-cell fusion [6-8]. By exploiting the in vitro abilities of each agent to potentially block the two major modes of HIV-1 transmission, PRO 542:T-20 combinations may prove to be particularly effective in vivo.

PRO 542 and T-20 synergistically inhibited fusion mediated by R5, X4 and R5X4 virus envelopes. While the activity of PRO 542 against primary viruses is independent of their coreceptor usage [8], T-20's ability to block virus-cell fusion reportedly varies according coreceptor usage [14]. Additional studies with a broader panel of viruses are needed to determine if PRO 542:T-20 synergy is subtly affected by coreceptor usage.

PRO 542 alone was not able to trigger formation of the gp41 pre-hairpin intermediate, which formed only when Env, CD4 and coreceptor interacted at a fusion-permissive temperature. Thus synergy may derive from subtler events, such as the clustering of multiple gp120/gp41 trimers to

form the fusion pore [13]. At sub-neutralizing doses, PRO 542 may block a subset of Envs from interacting with target cells, while perhaps allowing other Envs to proceed to the pre-hairpin intermediate. The fusion intermediates may remain exposed and susceptible to T-20 for significantly longer periods of time, as required to recruit a critical number of free Envs to the site of the fusion pore. In a recent study, T-20 mediated 100% inhibition when added within the first 15 minutes of cell mixing but was essentially inactive (<10% inhibition) at 75 minutes [15]. Ongoing studies are examining the effects of PRO 542 during this time period.

Additional studies are exploring higher combinations of attachment, coreceptor and fusion inhibitors. Also, the present study employed only subtype B viruses. It will be important to determine if the combination inhibits HIV-1 in a genetic subtype-independent manner, as do PRO 542 and T-20 individually. Lastly, further studies will explore combinations of PRO 542 and T-20 against replication-competent viruses in primary cells both in vitro and in animal models of HIV-1 infection.

In summary, PRO 542 and T-20 were potently synergistic when used to inhibit HIV-1 entry in vitro. Cooperative inhibition of virus-cell and cell-cell fusion was observed for phenotypically diverse viruses and translated into meaningful dose reductions. These findings provide a strong rationale for evaluating combinations of these agents in vivo.

### References for Third Series of Experiments

1. Jacobson JM, Lowy I, Fletcher CV et al. Single-dose safety, pharmacology and antiviral activity of the human immunodeficiency virus (HIV) type 1 entry inhibitor PRO 542 in HIV-infected adults. *Journal of Infectious Diseases* **2000**; 182:326-329.
2. Shearer WT, Israel RJ, Starr S et al. Recombinant CD4-IgG2 in HIV-1 infected children: Phase I/II study. *Journal of Infectious Diseases* **2000**; 182:1774-1779.
3. Kilby JM, Hopkins S, Venetta TM et al. Potent suppression of HIV-1 replication in humans by T-20, a peptide inhibitor of gp41-mediated virus entry. *Nat Med* **1998**; 4:1302-1307.
4. Pilcher CD, Eron JJ, Ngo L et al. Prolonged therapy with the fusion inhibitor T-20 in combination with oral antiretroviral agents in an HIV-infected individual. *AIDS* **1999**; 13:2171-2173.
5. Allaway GP, Davis-Bruno KL, Beaudry GA et al. Expression and characterization of CD4-IgG2, a novel heterotetramer which neutralizes primary HIV-1 isolates. *AIDS Research and Human Retroviruses* **1995**; 11:533-539.
6. Wild CT, Shugars DC, Greenwell TK, McDanal CB, Matthews TJ. Peptides corresponding to a predictive alpha-helical domain of human immunodeficiency virus type 1 gp41 are potent inhibitors of virus infection. *Proc*

Natl Acad Sci U S A **1994**; 91:9770-9774.

7. Chan DC, Kim PS. HIV entry and its inhibition. Cell **1998**; 93:681-684.
8. Trkola A, Ketas T, KewalRamani VN et al. Neutralization sensitivity of human immunodeficiency virus type 1 primary isolates to antibodies and CD4-based reagents is independent of coreceptor usage. J Virol **1998**; 72:1876-1885.
9. Dragic T, Litwin V, Allaway GP et al. HIV-1 entry into CD4+ cells is mediated by the chemokine receptor CC-CKR-5. Nature **1996**; 381:667-673.
10. Litwin V, Nagashima KA, Ryder AM et al. Human immunodeficiency virus type 1 membrane fusion mediated by a laboratory-adapted strain and a primary isolate analyzed by resonance energy transfer. Journal of Virology **1996**; 70:6437-6441.
11. Chou TC, Talalay P. Quantitative analysis of dose-effect relationships: the combined effects of multiple drugs or enzyme inhibitors. Advances in Enzyme Regulation **1984**; 22:27-55.
12. Trkola A, Dragic T, Arthos J et al. CD4-dependent, antibody-sensitive interactions between HIV-1 and its co-receptor CCR-5. Nature **1996**; 384:184-187.
13. Fu YK et al., Physiochemical dissociation of CD4-mediated syncytium formation and shedding of human

immunodeficiency virus type 1 gp120. Journal of Virology 1993, 67:3838-3825.

5 14. Derdeyn CA, Decker JM, Sfakianos JN et al. Sensitivity of human immunodeficiency virus type 1 to the fusion inhibitor T-20 is modulated by coreceptor specificity defined by the V3 loop of gp120. Journal of Virology **2000**; 74:8358-8367.

10 15. Munoz-Barroso I, Durell S, Sakaguchi K, Appella E, Blumenthal R. Dilation of the human immunodeficiency virus-1 envelope glycoprotein fusion pore revealed by the inhibitory action of a synthetic peptide from gp41. J Cell Biol **1998**; 140:315-323.

15  
20

#### Fourth Series of Experiments

##### Mechanisms of synergy between HIV-1 Attachment, Coreceptor and Fusion Inhibitors

5 HIV-1 entry proceeds via a cascade of events that provide promising targets for a new generation of antiviral therapies, including the gp120-CD4 attachment inhibitor PRO542, the gp120-coreceptor inhibitor PRO140, and the gp41 fusion inhibitors T-20 and T-1249. The multi-step nature of  
10 HIV-1 entry leaves the virus highly susceptible to inhibition by combinations of drugs that act at distinct stages of this process. It has been shown that double and triple drug cocktails of attachment, coreceptor and the fusion inhibitors potently and synergistically block HIV-1  
15 entry over a wide range of experimental conditions in vitro.

The present study was performed in order to identify the molecular basis of the observed synergistic interactions. HIV-1 membrane fusion was monitored in real time using a  
20 semi-automatic fluorometric assay, and the inhibitory activities of the individual drugs and drug cocktails were evaluated in time-of-addition, washout, and stepwise temperature-controlled studies. The data were consistent with a model wherein the drugs act cooperatively to delay  
25 the recruitment of a critical number of fusion-active HIV-1 envelope glycoproteins to the site of the fusion pore. These findings have important implications for the combination use of HIV-1 entry inhibitors in vivo, which may emerge as an important new paradigm for antiviral therapy.

30 As shown in Figure 11, HIV-1 entry involves at least three steps that provide targets for therapy: (1) gp120-CD4



attachment; (2) gp120-coreceptor interactions; and (3) gp41-mediated fusion.

5 The CD4-IgG2 attachment inhibitor (PRO 542), as shown in Figure 12. Is a tetravalent CD4-based protein. It broadly and potentially neutralizes primary HIV isolates in vitro, ex vivo and in vivo, and acts prior to fusion. PRO542 has completed two phase I/II clinical trials, showing (1) excellent safety and pharmacokinetic profiles and that it is  
10 non-immunogenic; (2) statistically significant reductions in viral load with a single dose; and (3) sustained reductions in free and cell-associated infectious virus. PRO 542 is in Phase II testing.

15 The PRO 140 coreceptor inhibitor, as shown in Figure 13, is a monoclonal antibody to CCR5. It potentially neutralizes CCR5-using virus. It protects primary T cells and macrophages, and its inhibition is genetic subtype-independent. It selectively blocks HIV entry without affecting chemokine-  
20 induced signaling. There has been no emergence of HIV resistance following 31 weeks in vitro culture.

The T-20 fusion inhibitor, as shown in 14, is a peptide derived from HIV-1 gp41. It broadly and potentially blocks HIV-  
25 1 cell-cell and cell-virus fusion in vitro. It has completed Phase I/II clinical trials, showing (1) good tolerability; (2) pK supports twice daily subcutaneous dosing; and (3) clinically significant dose-dependent reductions in viral load.

Combination Use of Entry Inhibitors

Combination therapy may be required to control HIV in vivo. HIV entry inhibitors may represent the next major advance in therapy. It is critical to determine drug-drug interactions earlier rather than later in clinical development to avoid antagonistic combinations and identify synergistic combinations. The clinical benefits of synergistic combinations include more potent antiviral effects and more durable antiviral effects.

An HIV-1 virus-cell fusion assay is described in Figure 15. In a single-cycle HIV-1 entry assay, Env-Luc+ HIV reporter viruses were prepared as described [1]. The viruses are complemented with gp120/gp41 from an HIV strain of interest and thus are capable of fusing with target cells that express CD4 and fusion coreceptors, resulting in the introduction of the viral genes into the cell. Because the viruses encode the luciferase reporter enzyme rather than HIVenv, infection leads to the production of luciferase rather than new viral particles. The amount of luciferase is measured 72 hours post-infection using standard methods.

Figures 16 and 17 demonstrate the synergistic inhibition of virus-cell fusion with PRO542 and T-20.

An HIV-1 cell-cell fusion assay is described in Figure 18. Such assay is a Resonance Energy Transfer (RET) assay of HIV-1 membrane fusion. Cells expressing gp120/gp41 (ENV cells) are labeled with the fluorescent dye octadecyl fluorescein (F18), while T cell that express CD4 and fusion coreceptors (CD4 cells) are labeled with octadecyl rhodamine (R18). The emission spectrum of F18 overlaps with the

excitation spectrum of R18, allowing fluorescence RET to occur when the dyes are placed in the same membrane following fusion. RET is measured by stimulating F18 at 450nm and measuring the R18 emission at 590nm. The RET signal is directly related to the amount of HIV-1 fusion [2].

Figures 19 and 20 demonstrate the synergistic inhibition of cell-cell fusion with PRO542 and T-20.

Figures 21 and 22 demonstrates that the PRO140, PRO542 and T-20 triple combination synergistically blocks HIV-1 entry.

Figure 23 demonstrates that PRO542 does not potentiate T-20 activity in the absence of coreceptor. PRO542, T-20 or a 1:2 mixture were pre-incubated with HeLa-ENVJR-FL cells for 2 hours at 37°C prior to washing, addition of PM1 target cells, and completion of the fusion assay.

Formation of the prehairpin intermediates may need CD4, coreceptor and 37°C, as demonstrated in Figures 24 and 25.

Figures 26 and 27 describe a possible mechanism of synergy, wherein PRO542 increases the half-life of the T-20 targets.

Figure 28 demonstrates synergistic inhibition of HIV-1 entry using PRO542, T-1249 and in a 1:10 molar combination in an env-mediated membrane fusion (RET) assay. Figure 29 demonstrates the combination indices and dose reductions for a 1:10 molar combination of PRO542 and T-1249.

#### References for Fourth Series of Experiments:

1. Dragic et al, Nature 381:667.
2. Litwin et al., J. Virol. 70:6437.